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A brief bibliometric analysis of Web of Science publications on "Carbon" topic for 2019–2020

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Abstract. A brief bibliometric analysis of 5,000 most cited scientific publications presented in the Web of Science database on the "Carbon" topic for 2019–2020 is done. It is shown that the world's leading scientific centers of China, the United States, India, South Korea, Japan and Germany, as well as the Russian Academy of Sciences are involved in research on this topic. The following areas of scientific research were dominant: materials science, physical chemistry, nanotechnology, engineering chemistry, applied physics, energy, electrochemistry, ecology, condensed matter physics.

The clustering method based on the co-occurrence of the Author Keywords and the Keywords Plus of the Web of Science system revealed six areas of research: 1. catalysis, hydrogen production, carbon materials doped with nitrogen; 2. graphite/graphene-based energy storage systems; 3. sensors and emissions based on carbon quantum dots; 4. nanocomposites and their physical properties; 5. energy consumption and climate change; 6. adsorption and organic pollutants.

The author assumes the high potential of research on the co-production of hydrogen and graphite, which may combine the interests of hydrogen energy development and production of new materials.

Keywords: bibliometric analysis, Web of Science, scientometrics, carbon, graphene, hydrogen, catalysis, nanocomposites, energy storages.

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Introduction

The Paris Climate Agreement aims to keep global warming well below two degrees Celsius, which imposes limits on greenhouse gas emissions[1].

On the other hand, the United Nations Sustainable Development Goal 7 (SDG7) implies universal access to affordable, reliable, sustainable and modern energy sources[2]. The energy sector (electricity, heat and transport) is responsible for 73.2% of greenhouse gas emissions[3].

A compromise in solving these problems can be achieved by co-producing hydrogen and carbon from fossil energy sources, which does not require the utilization of carbon dioxide (CO_2), especially from natural gas.

For example, the leading corporations of Russia's fuel and energy sector consider methane pyrolysis technology a promising way to enable the production of hydrogen and pure carbon[4].

While the subject of hydrogen economy is well researched [1–3], the "production of materials based on carbon" direction is underrepresented in oil and gas studies. Thus, the query "carbon" in OnePetro, the online library of technical literature for the oil and gas industry, gets 17,327(2,702) publications for 2011–2020, while the query "carbon dioxide" OR "carbon capture" gets 7,080(1,175) papers, and the queries "carbon nanotube" and "graphene" get only 205 and 249(42) results respectively.

[1] The Paris Agreement. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement
[2] Goal 7: Affordable and clean energy. https://www.un.org/sustainabledevelopment/energy/
[3] Sector by sector: where do global greenhouse gas emissions come from? https://ourworldindata.org/emissions-by-sector
[4] Russia in the global hydrogen race. https://www.swp-berlin.org/en/publication/russia-in-the-global-hydrogen-race/

The number in parentheses refers to the articles in peer-reviewed journals. For comparison, in the Web of Science Core Collection, the queries: TOPIC: ("carbon nanotube") and TOPIC: (graphene) get 125,350 and 217,689 results for the given years respectively.

To reduce the biases associated with a single abstract database and a broad query, TOPIC, I present for comparison the data of The Lens database by the narrow queries: "Filters: Year Published = (2011–2020) Keyword = (Carbon Nanotubes)" obtains 2,624 records, while "Keyword = (Graphene)" obtains 5,783 records for the same period. To illustrate the topics of publications, I present graphs of the data in the "Fields of Study" and "Subject" fields for each of the queries (Fig. 1, 2).

a

b

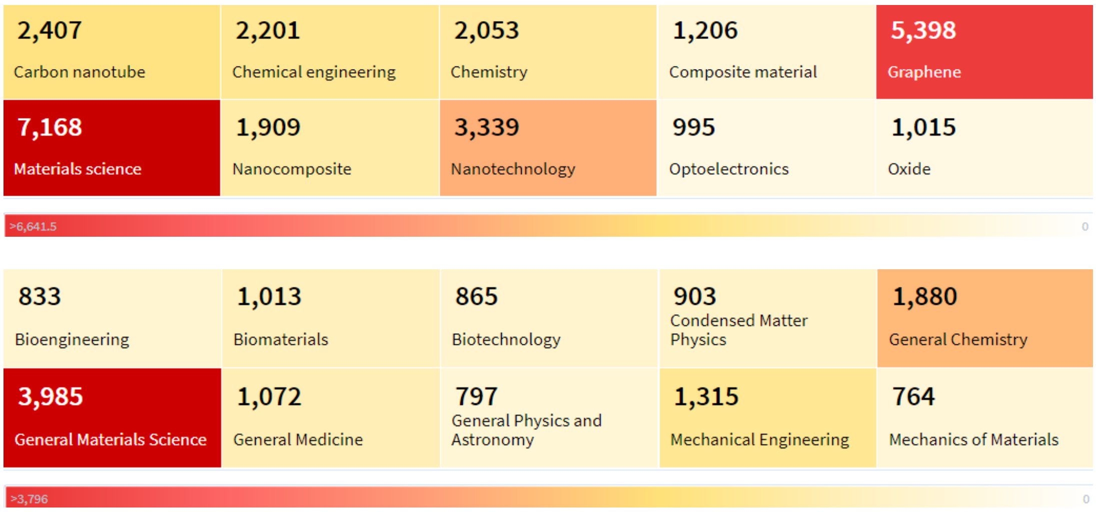

Fig. 1. Distribution of publication topics for the query "Keyword = (Carbon Nanotubes)" by the fields: a – "Fields of Study", b – "Subject"

a

b

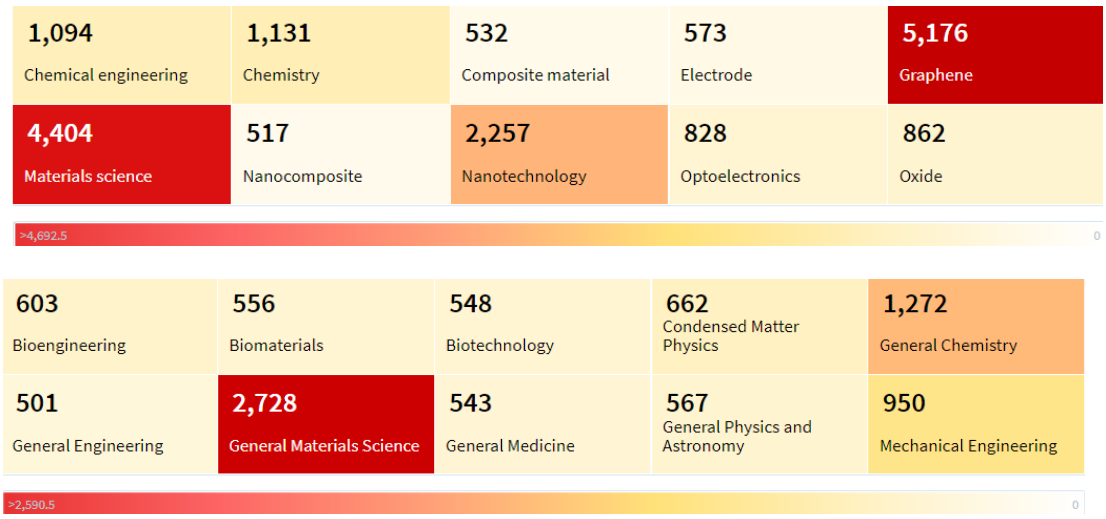

Fig. 2. Distribution of publication topics for the query "Keyword = (Graphene)" by the fields: a – "Fields of Study", b – "Subject"

In any data slice, the dominant topics are materials science, graphene, carbon nanotubes, nanotechnology, condensed state physics and composites.

Such a huge number of peer-reviewed publications on the above queries aligns well with industry needs; for example, the carbon fiber market is expected to grow from $4.7 billion in 2019 to $13.3 billion by 2029, at an average annual growth rate of 11.0% over the period from 2019 to 2029[5].

The global graphene market was estimated at $78.7 million in 2019 and is expected to grow at a compound annual growth rate of 38.7% from 2020 to 2027[6].

For the Russian fuel and energy sector, the rapidly developing market for carbon-based materials can be of great interest, so it is advisable to analyze the picture of scientific research on this topic.

Materials

To build an overall picture of carbon-related scientific publications and to reduce selection biases, bibliometric data from the Web of Science (WoS) reference database were retrieved by the most general query:

TITLE: (carbon) and Timespan: 2019–2020 and Indexes: SCI-EXPANDED, ESCI.

A total of 58,924 results were obtained at the time of the query (28.10.2020). For further bibliometric analysis, I selected 5,000 most cited publications. At the same time, the bulk of the publications – 4,598 articles – falls on 2019, the papers of 2020 are not indexed in full, so the citation can only be evaluated later.

The choice of the base query was derived from the analysis of the test query data. The total number of publications indexed in the WoS for 2011–2020 for the query “carbon* OR graphene*” was:

– 1,125,785 publications when searching by all fields of the database;

– 1,074,048 documents when searching by the titles, Author Keywords and Keywords Plus (the index terms generated by the WoS by in-depth analysis of the references of the articles).

– 381,641 publications when narrowing the search to the presence of “carbon* OR graphene*” only in the titles.

By removing “graphene*” from the query, I reduced the focus of interest on a specific type of material, by limiting the time interval to 2019–2020, I focused the interest on recent publications, which corresponds to the main objective of this paper: to analyze the current landscape of scientific publications on the topic “Carbon”.

The data from The Lens platform were additionally used to demonstrate the independence of the obtained results from the chosen abstract database.

Methods

Following the aim of this study – to build the overall picture of carbon-related scientific publications – I used only bibliometric methods for assessing the co-occurrence of the sum of Author Keywords and Keywords Plus (clustering), as well as some data from the “Analysis of results” section of the WoS. For keyword clustering, I used the VOSviewer scientometric and bibliometric software [4, 5]. The total number of unique keywords in 5,000 publications were 18,985, with 975 words occurring more than nine times. The parameter of the minimum number of words in the cluster was chosen to be 100. The stability of clustering was checked by changing this parameter by ±20%. This resulted in the identification of six clusters.

Keywords and other terms in the tables are given as they appear in the bibliometric data, enabling to use them in a further selection of materials by subject specialists.

For each cluster, I give examples of references to highly cited publications that illustrate the subject of this cluster well.

[5]Global carbon fiber market size. https://www.whatech.com/markets-research/materials-chemicals/705441-carbon-fiber-market-by-raw-material-pan-pitch-rayon-fiber-type-virgin-recycled-product-type-modulus-application-composite-non-composite-end-use-industry

[6]Graphene market size. https://www.grandviewresearch.com/industry-analysis/graphene-industry

General bibliometric data on 58,924 publications

The processing of 58,924 bibliometric data gathered by the query: “TITLE: (carbon) and Timespan: 2019–2020 and Indexes: SCI-EXPANDED, ESCI” revealed the distribution of publication activity by country and source of funding (Table 1).

Table 1

Distribution of publication activity by country and funding sources

Countries	Records	Funding Agencies	Records
Peoples R China	26,488	National Natural Science Foundation of China NSFC	18,356
USA	8,167	Fundamental Research Funds for the Central Universities	2,938
India	3,610	National Key Research and Development Program of China	1,688
South Korea	2,985	China Postdoctoral Science Foundation	1,679
Japan	2,778	National Science Foundation NSF	1,569
Germany	2,663	National Key R&D Program of China	1,234
Iran	2,213	Ministry of Education Culture Sports Science and Technology Japan MEXT	1,032
England	2,183	European Union EU	922
Australia	2,155	Japan Society for the Promotion of Science	880
Canada	1,590	United States Department of Energy DOE	865
Russia	**1,575**	Natural Science Foundation of Jiangsu Province	798
France	1,555	China Scholarship Council	790
Spain	1,411	National Council for Scientific and Technological Development CNPG	703
Italy	1,263	Australian Research Council	641
Brazil	1,247	Chinese Academy of Sciences	641
Saudi Arabia	950	CAPES	633
Turkey	910	German Research Foundation DFG	626
Taiwan	897	Natural Science Foundation of Shandong Province	615
Malaysia	852	Natural Sciences and Engineering Research Council of Canada	595
Poland	838	Grants-in-Aid for Scientific Research (KAKENHI)	586

Table 1 indicates that the dominance of carbon-related publications from China correlates well with the list of funders, which are also predominantly Chinese. India has good publication activity, largely due to extensive collaboration with other countries. The US and European researchers also rely on good funding: National Science Foundation; European Union; United States Department of Energy (DOE); German Research Foundation. Research in Japan is supported by Ministry of Education, Culture, Sports Science and Technology Japan (MEXT) and Grants-in-Aid for Scientific Research (KAKENHI).

The fact that Russia occupies an intermediate position between Canada and France indicates that Russian researchers pay considerable attention to the topic in question. Two factors should be taken into account: less involvement of Russian research institutions in international cooperation compared to the institutions of China, the United States and Europe, and the fact that a significant part of the research results is published in Russian-language journals that are not indexed in the Web of Science.

Worth noting is the high publication activity of Iran, which is under stronger sanctions than Russia but is better represented in the publications in highly ranked journals.

Most frequent are the publications in these seven languages (of the total number of 58,924): English (58,147); Chinese (333); Spanish (77); Korean (76); Russian (67); German (66); Japanese (44).

Further, I analyzed the distribution of publication activity by the WoS categories and journal titles (Table 2). Table 2 indicates that the WoS categories are dominated by sections related to materials science, chemistry, condensed state physics, metallurgy, polymers, nanotechnology and energy. The journal titles in the second column of the table agree well with the WoS categories, with journals publishing articles on various topics in chemistry and materials science predominating. Of particular note is the International Journal of Hydrogen Energy (h-index=202), which is the official publication of the International Association for Hydrogen Energy. Sections on "hydrogen fuel cells", "electrolysis of water to produce hydrogen" and "hydrogen storage using nanomaterials" all involve the development of new materials based on various forms of graphite.

Table 2

Distribution of publication activity by the WoS categories and journal titles

WoS categories	Records	Source titles	Records
Materials Science Multidisciplinary	14,171	Carbon (Q1)	974
Chemistry Physical	10,243	Chemical Engineering Journal (Q1)	737
Chemistry Multidisciplinary	7,808	Applied Surface Science (Q1)	732
Environmental Sciences	6,499	Electrochimica Acta (Q1)	722
Nanoscience Nanotechnology	5,323	ACS Applied Materials Interfaces (Q1)	693
Engineering Chemical	5,186	Journal of Cleaner Production (Q1)	672
Physics Applied	5,030	Science of the Total Environment (Q1)	645
Energy Fuels	4,841	Journal of Alloys and Compounds (Q1)	639
Electrochemistry	3,856	Journal of Materials Chemistry A (Q1)	622
Engineering Environmental	3,088	RSC Advances (Q2)	552
Physics Condensed Matter	3,023	ACS Sustainable Chemistry Engineering (Q1)	487
Chemistry Analytical	2,514	Abstracts of Papers of the American Chemical Society	485
Green Sustainable Science Technology	2,302	**International Journal of Hydrogen Energy (Q2)**	451
Metallurgy Metallurgical Engineering	1,885	Environmental Science and Pollution Research (Q2)	443
Polymer Science	1,822	Scientific Reports (Q1)	441
Multidisciplinary Sciences	1,632	Journal of Colloid and Interface Science (Q1)	439
Materials Science Coatings Films	1,589	Materials (Q2)	403
Materials Science Composites	1,566	Journal of Power Sources (Q1)	378
Geosciences Multidisciplinary	1,112	Nanoscale (Q1)	354
Soil Science	1,059	Nanomaterials (Q1)	337

Note: Journal quartile membership was determined by the Journal Citation Reports category with the highest score in the WoS.

Ten organizations/affiliations with the highest publication activity are: Chinese Academy of Sciences (3897); University of Chinese Academy of Sciences CAS (1,394); Centre national de la recherche scientifique (1,070); *Russian Academy of Sciences (827)*; University of California System (800); United States Department of Energy (794); Indian Institute of Technology System (748); Tsinghua University (671); University of Science Technology of China (574); Helmholtz Association (569).

Bibliometric analysis of the 5,000 most highly cited articles revealing the dominant areas of research

Research topics are described well both by Author Keywords and by Keywords Plus generated by the WoS system (Table 3). Table 3 indicates that the most frequent are the keywords associated with graphene, carbon nanomaterials, graphene oxide, carbon nanotubes, nanocomposites and graphene quantum dots.

Table 3

The 40 most frequent keywords in 5,000 highly cited publications 2019–2020 (data retrieved 28.10.2020)

Keyword	Occurrence	Keyword	Occurrence
performance**	804	catalysts	209
graphene*	766	carbon nanotubes*	198
nanoparticles*	669	oxide	195
nanosheets*	500	oxygen reduction reaction	188
nitrogen	361	removal	178
adsorption	328	supercapacitor***	178
porous carbon*	318	storage***	175
water	316	degradation	170
nanotubes*	315	reduced graphene oxide	165
composite	314	metal-organic frameworks	163
composites	284	energy	162
activated carbon	278	oxidation	162
graphene oxide*	258	biomass	161
facile synthesis	254	energy-storage***	161
nanocomposites*	251	quantum dots*	161
efficient	242	nanocomposite*	156
fabrication	238	graphene quantum dots*	152
reduction	227	high-performance**	150
electrode	217	oxygen reduction	144
electrodes	216	behavior	143

Note: the single (*), double (**) and triple (***) asterisks indicate terms that might be conventionally assigned to the same cluster. For example: supercapacitor***, storage***, energy-storage***.

The keyword "performance" comes first in terms of frequency; the examples of phrases with it in the full texts are: catalytic performance, high-performance lithium-sulfur batteries, electromechanical performance, electrocatalytic performance, photocatalytic performance, electrochemical performance, storage performance, high-performance anode materials, high-performance composites. This indicates the high importance of the examined subject for applied research, which is also confirmed by such keywords as: manufacturing, supercapacitor, storage, degradation, metal-organic framework, energy accumulation.

Clustering of keywords based on their co-occurrence in the 5,000 most cited publications

For a detailed study of the "Carbon" topic, I used the clustering of keywords based on their co-occurrence in the 5,000 most cited publications.

VOSviewer, a program designed to build and visualize bibliometric data networks, was used for keyword clustering.

Keyword clustering (Author + KeyWords Plus) was performed under the following conditions: out of 18,985 keywords, 975 keywords were selected that occurred more than nine times, while each cluster included at least 100 keywords.

Six clusters were obtained:

1. catalysis, hydrogen-production, nitrogen-doped carbon;
2. graphite/graphene-based energy storage systems;
3. sensors and emissions based on carbon quantum dots;
4. nanocomposites and their physical properties;
5. energy consumption and climate change;
6. adsorption and organic pollutants.

Their main features are presented below in tables and graphs. The stability of clustering was checked by changing of the minimum number of keywords in the cluster by ±20%.

In compiling the summary tables for each of the six clusters, 40 of the most frequent keywords were selected and used to describe the cluster theme.

The tables contain the following fields: label (keyword name), keyword occurrence and the average citation of the publications in which this keyword appears.

It should be noted that the average citation of a keyword is determined by the average citation of the articles whose entries contain this term in the Author keywords and Keywords Plus fields. This value can be retrieved from the GML files generated by VOSViewer.

In addition to the tables, graphs of the relationships between terms are presented for the two most frequent terms in each cluster. Such data presentation makes it possible to demonstrate the relationship between terms not only within a cluster but also between clusters.

The results of the bibliometric analysis for the first cluster are presented in Table 4 and Fig. 3 and 4.

Table 4

The 40 most frequent keywords within the Cluster 1 and the average citations of publications associated with a keyword

Label	Occurrence	Average citations	Label	Occurrence	Average citations
nitrogen^	361	23.2	electrocatalysis*	88	**26.0**
water	316	22.5	iron	86	20.9
facile synthesis	254	23.5	oxygen**	85	23.0
efficient	242	23.3	co_2 reduction	84	25.7
reduction	227	21.2	electrocatalyst*	82	23.0
catalysts*	209	22.9	hydrogen evolution** reaction	79	25.3
oxygen reduction** reaction	188	**26.4**	active-sites	77	25.9
degradation	170	20.0	sulfur	75	21.7
metal-organic frameworks	163	25.0	TIO_2	74	17.7
oxidation**	162	20.6	construction	71	24.9
oxygen reduction**	144	25.1	dioxide	69	21.4
catalyst*	140	20.6	oxygen evolution reaction	67	24.3
electrocatalysts*	137	**27.3**	CO	66	19.7
evolution	136	24.8	nitrogen-doped carbon^	64	23.0
highly efficient	132	23.0	doped carbon	62	23.8
conversion	130	21.0	hydrogen**	62	20.7
hydrogen evolution**	130	**30.5**	carbon nitride^	58	**27.3**
metal-organic framework	127	20.8	g-C_3N_4 nanosheets^	58	22.9
photocatalysis*	123	**26.0**	graphitic carbon nitride^	58	23.5
g-C_3N_4^	103	22.6	N-doped carbon^	58	22.5

Note: Contextually related terms are marked by the symbols * and **. Nitrogen-related terms are marked by the symbol ^.

This cluster can be conditionally labelled “Catalysis, hydrogen-production, nitrogen-doped carbon”. Several categories of keywords correspond with this label: electrocatalysis, photocatalysis, hydrogen evolution, oxygen evolution reaction, as well as the most cited publications mentioning electro- and photocatalysis, hydrogen evolution [6, 7]; the keywords related to carbon nitride (carbon nitride, graphitic carbon nitride, nanosheets, g-C_3N_4) and the corresponding publications [8–11]. Noteworthy is the frequent mention of nitrogen-doped carbon, which is considered to be a promising type of cathode catalyst [12–15].

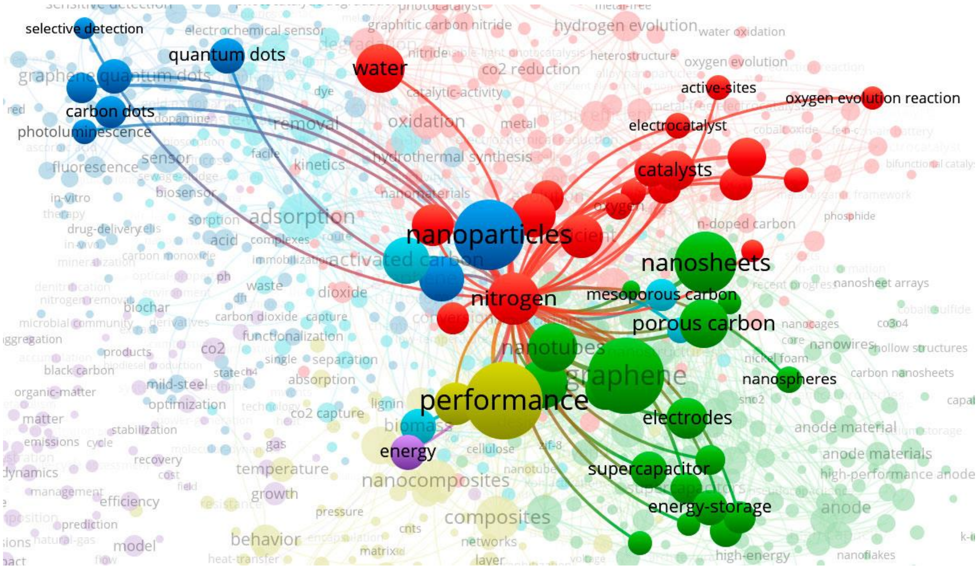

Fig. 3. Cluster 1. The main links of the term “nitrogen” with the other terms

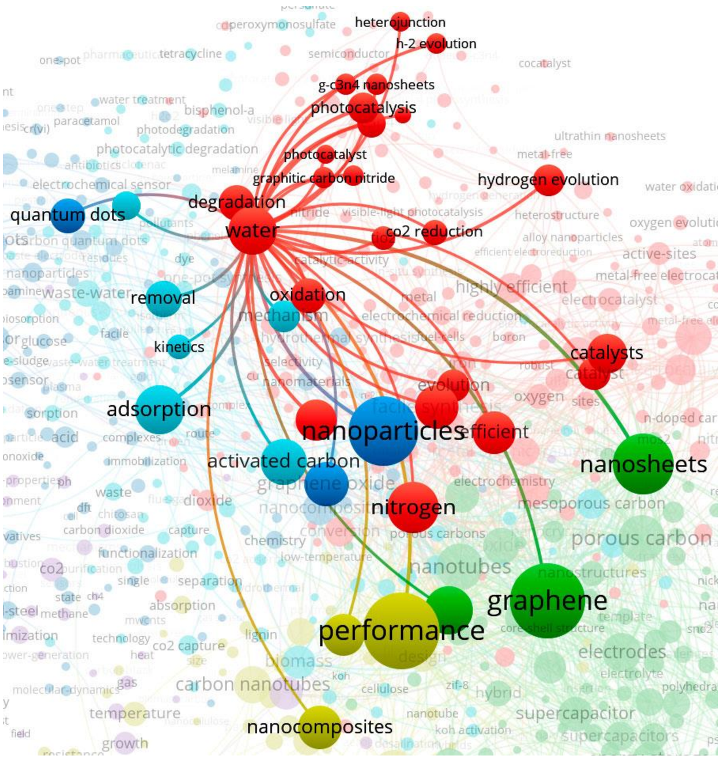

Fig. 4. Cluster 1. The main links of the term “water” with the other terms

The results of the bibliometric analysis for the second cluster are presented in Table 5 and Fig. 5 and 6.

Table 5

The 40 most frequent keywords within the Cluster 2 and the average citations of publications associated with a keyword

Label	Occurrence	Average citations	Label	Occurrence	Average citations
graphene*	766	22.0	high-capacity**	107	23.8
nanosheets*	500	23.3	lithium**	107	23.2
porous carbon*	318	23.9	hybrid	98	22.4
nanotubes*	315	21.3	nanostructures*	94	23.6
composite	314	21.6	carbon	89	23.0
electrode**	217	22.5	nanospheres*	88	24.6
electrodes**	216	23.8	anode materials**	82	25.1
oxide	195	20.6	batteries**	80	24.5
supercapacitor**	178	19.1	capacity**	80	22.3
storage**	175	21.8	arrays	79	22.8
reduced graphene oxide	165	22.7	anode material**	78	23.0
energy-storage**	161	23.5	spheres	77	19.6
high-performance	150	23.8	capacitance**	74	20.8
anode**	132	22.6	nanocrystals	73	23.1
cathode**	130	21.0	sodium-ion batteries	73	26.6
electrochemical performance**	128	22.4	doped graphene*	69	27.7
supercapacitors**	127	18.4	graphite	69	22.4
electrode materials**	114	20.3	hierarchical porous carbon	67	19.0
nanofibers*	114	24.8	lithium-ion**	64	23.5
microspheres	112	27.4	shell	64	22.2

Note: Contextually related terms are marked by the symbols * and **.

The conditional name for the cluster is “Graphite/graphene-based energy storage systems”. Corresponding keywords: graphene, porous carbon, nanotubes, nanostructures, nano-particles, nanocrystals, doped graphene, electrode materials, anode, cathode, electrochemical characteristics, supercapacitors, high capacity, lithium, sodium-ion and lithium-ion batteries.

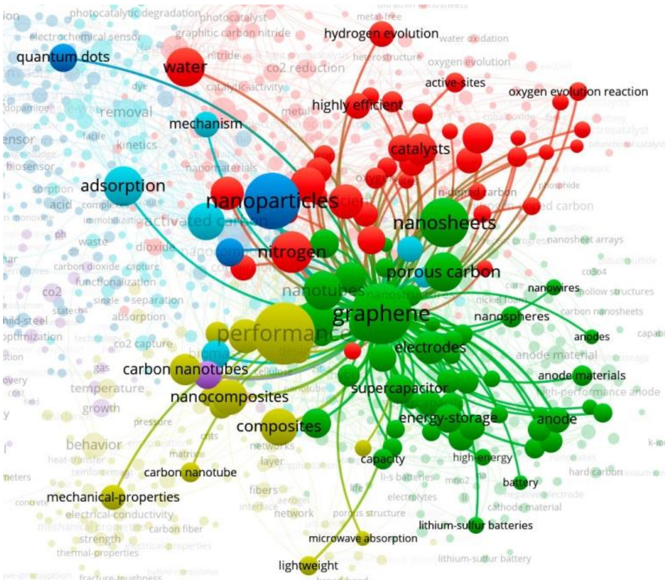

Fig. 5. Cluster 2. The main links of the term “graphene” with the other terms

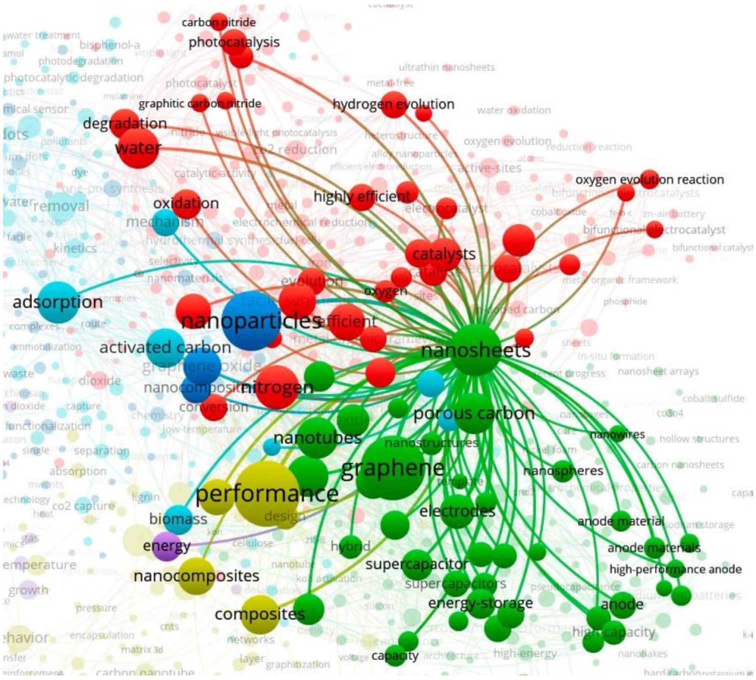

Fig. 6. Cluster 2. The main links of the term "nanosheets" with the other terms

This cluster is represented by the publications [16–21].

The results of the bibliometric analysis for the third cluster are presented in Table 6 and Fig. 7 and 8.

Table 6

The 40 most frequent keywords within the Cluster 3 and the average citations of publications associated with a keyword

Label	Occurrence	Average citations	Label	Occurrence	Average citations
nanoparticles	669	20.4	chemistry	48	19.3
graphene oxide	258	23.2	mild-steel	47	16.5
quantum dots*	161	20.8	green	46	20.5
nanocomposite	156	19.9	emission	45	16.2
graphene quantum dots*	152	21.5	functionalization	44	20.0
carbon dots*	130	19.4	ions	44	18.6
sensor**	119	17.1	biosensor**	41	19.1
nanodots*	115	18.2	luminescence**	41	19.5
green synthesis	83	20.5	hydrogen-peroxide	40	18.4
photoluminescence**	79	18.2	electrochemical sensor**	37	16.3
sensitive detection**	73	19.6	ascorbic-acid	34	19.1
one-step synthesis	67	31.0	glucose	33	17.9
acid	66	18.2	voltammetric determination**	33	17.6
fluorescence**	65	17.7	probe**	32	17.3
hydrothermal synthesis	63	20.0	label-free detection	31	34.6
one-pot synthesis	62	28.4	dopamine	30	16.8
carbon quantum dots*	58	23.3	extraction	30	16.9
gold nanoparticles	58	21.2	sensors**	30	17.9
selective detection**	58	18.3	complexes	29	17.0
nanomaterials	51	19.5	derivatives	29	15.7

Note: Contextually related terms are marked by the symbols * and **.

The conditional name for the cluster is "Sensors and emissions based on carbon quantum dots". Corresponding keywords: graphene/carbon quantum dots, nanodots, sensors, selective detection, biosensor, electrochemical sensors, voltammetric determination, probe, label-free detection, fluorescence, luminescence.

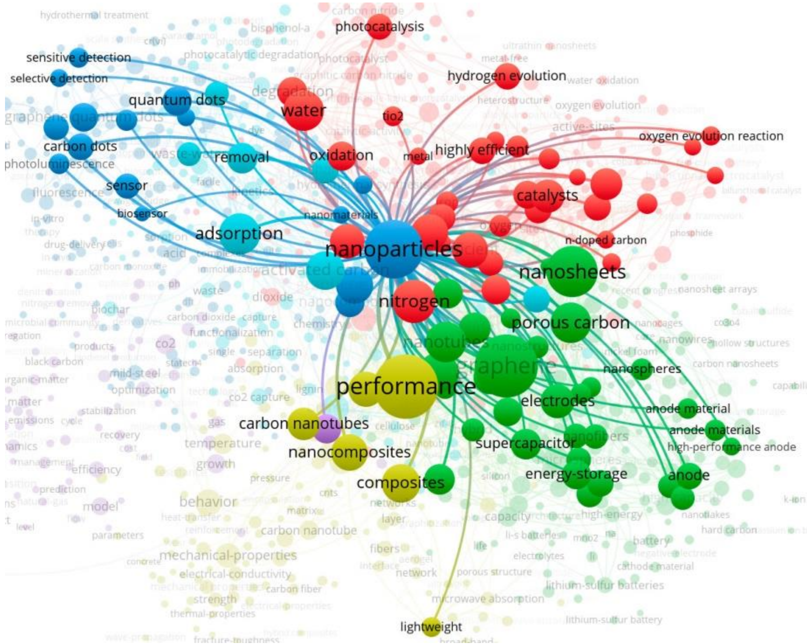

Fig. 7. Cluster 3. The main links of the term "nanoparticles" with the other terms

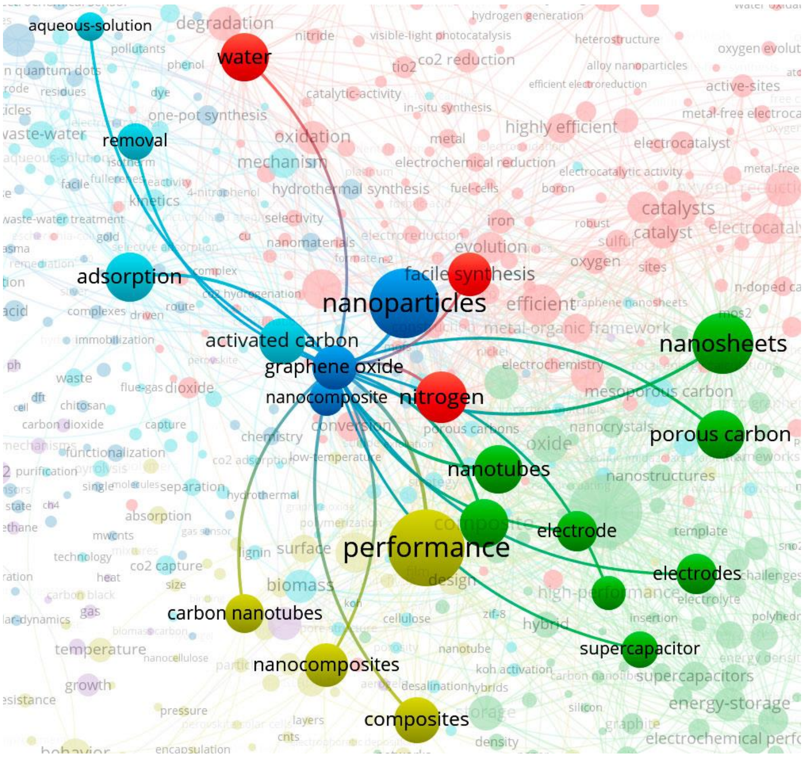

Fig. 8. Cluster 3. The main links of the term "graphene oxide" with the other terms

This cluster is represented by the publications [22–27].

The results of the bibliometric analysis for the fourth cluster are presented in Table 7 and Fig. 9 and 10.

Table 7

The 40 most frequent keywords within the Cluster 4
and the average citations of publications associated with a keyword

Label	Occurrence	Average citations	Label	Occurrence	Average citations
performance	804	21.1	electrical-conductivity**	45	23.1
composites*	284	21.4	microstructure**	43	19.9
nanocomposites*	251	22.0	morphology**	43	18.6
fabrication	238	20.3	strength**	43	17.4
carbon nanotubes*	198	20.9	layer	42	20.3
behavior**	143	17.8	mechanical properties**	41	20.3
mechanical-properties**	126	19.1	networks	41	23.0
design**	121	21.5	dispersion**	40	16.3
stability**	116	18.9	microwave absorption**	39	29.1
surface	114	17.9	deposition	36	20.4
temperature**	88	22.2	particles	35	18.1
carbon nanotube*	78	16.3	thermal-conductivity**	34	22.4
lightweight	72	25.5	polymers*	33	25.8
enhancement	70	22.9	network	31	19.5
films	68	22.6	polymer composites*	31	18.9
conductivity	58	20.1	resistance**	31	19.4
fibers	54	24.3	thin-films	31	24.0
foam	53	20.2	matrix	30	22.0
polymer	50	19.4	surface modification**	30	25.0
absorption	48	21.0	carbon fiber*	28	17.4

Note: Contextually related terms are marked by the symbols * and **.

The conditional name for the cluster is “Nanocomposites and their physical properties”. Corresponding keywords: composites, nanocomposites, carbon nanotubes, polymer composites, thin-films, carbon fiber, electrical properties, elastic properties, mechanical properties, thermal-properties, stability, surface, temperature, light weight, conductivity, absorption, electrical conductivity, microstructure, strength, electromagnetic-wave absorption, resistance, surface modification, fabrication, design.

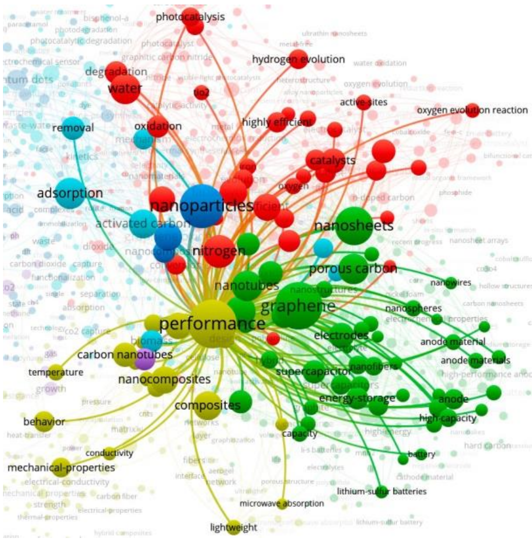

Fig. 9. Cluster 4. The main links of the term “performance” with the other terms

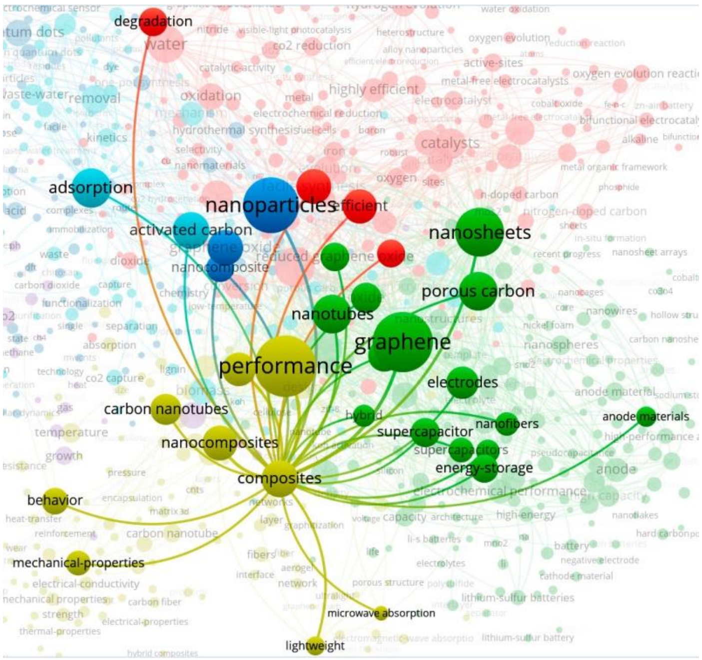

Fig. 10. Cluster 4. The main links of the term "composites" with the other terms

This cluster is represented by the publications [28–32].

The results of the bibliometric analysis for the fifth cluster are presented in Table 8 and Fig. 11 and 12.

Table 8

The 40 most frequent keywords within the Cluster 5 and the average citations of publications associated with a keyword

Label	Occurrence	Average citations	Label	Occurrence	Average citations
energy*	162	21.2	matter	34	19.0
CO_2 emissions**	115	22.4	system	34	17.8
CO_2**	84	19.6	greenhouse-gas** emissions	33	15.9
growth	75	21.3	gas**	31	16.4
model	69	17.6	sequestration	31	16.2
energy-consumption*	54	22.3	carbon dioxide**	29	23.2
efficiency*	53	18.6	management	29	16.4
climate-change**	49	21.1	emissions**	28	17.1
optimization*	49	17.3	organic-matter	28	17.1
impact**	48	16.6	pH	28	19.4
China**	46	19.3	black carbon	27	16.0
decomposition	43	18.7	financial development	26	26.2
transport*	40	21.1	methane**	26	16.2
dynamics	39	15.9	optical-properties	25	16.7
dioxide emissions**	38	25.1	urbanization	25	19.4
mechanisms	36	22.0	aerogels	24	22.3
renewable energy*	36	24.6	climate change**	24	16.5
environmental kuznets curve**	35	29.2	life-cycle assessment	23	18.7
carbon emissions**	34	22.4	recovery	23	20.0
economic-growth*	34	19.4	systems	23	14.5

Note: Contextually related terms are marked by the symbols * and **.

The conditional name of the cluster is "Energy consumption and climate change". Corresponding keywords: energy consumption, efficiency, optimization, transport, renewable energy, management, financial development, economic growth, urbanization, life-cycle assessment, CO_2 emissions, environmental Kuznets curve, climate change.

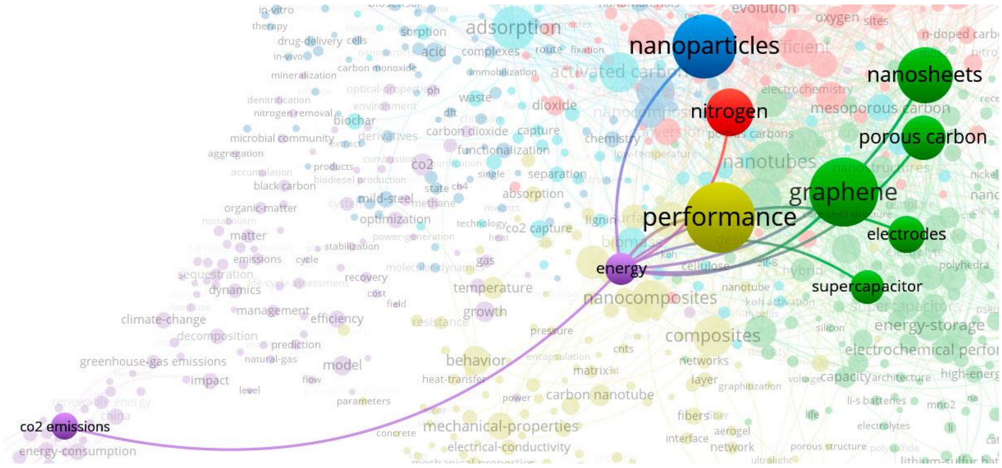

Fig. 11. Cluster 5. The main links of the term "energy" with the other terms

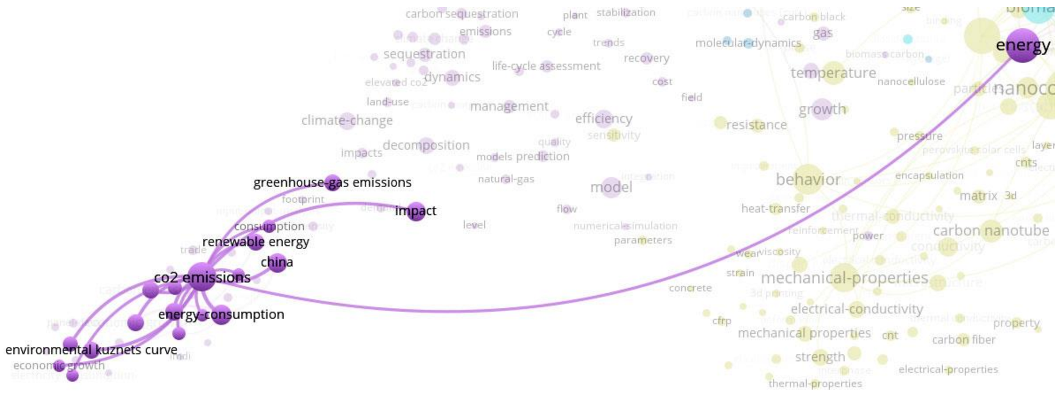

Fig. 12. Cluster 5. The main links of the term "CO_2 emissions" with the other terms

This cluster is represented by the publications [33–37].

The results of the bibliometric analysis for the sixth cluster are presented in Table 9 and Fig. 13 and 14.

Table 9

The 40 most frequent keywords within the Cluster 6 and the average citations of publications associated with a keyword

Label	Occurrence	Average citations	Label	Occurrence	Average citations
1	2	3	4	5	6
nitrogen^	361	23.2	electrocatalysis*	88	**26.0**
water	316	22.5	iron	86	20.9
facile synthesis	254	23.5	oxygen**	85	23.0
efficient	242	23.3	CO_2 reduction	84	25.7
reduction	227	21.2	electrocatalyst*	82	23.0
catalysts*	209	22.9	hydrogen evolution** reaction	79	25.3
oxygen reduction** reaction	188	**26.4**	active-sites	77	25.9
degradation	170	20.0	sulfur	75	21.7
metal-organic frameworks	163	25.0	TiO_2	74	17.7
oxidation**	162	20.6	construction	71	24.9

Table 9 continued

1	2	3	4	5	6
oxygen reduction**	144	25.1	dioxide	69	21.4
catalyst*	140	20.6	oxygen evolution reaction	67	24.3
electrocatalysts*	137	**27.3**	CO	66	19.7
evolution	136	24.8	nitrogen-doped carbon^	64	23.0
highly efficient	132	23.0	doped carbon	62	23.8
conversion	130	21.0	hydrogen**	62	20.7
hydrogen evolution**	130	**30.5**	carbon nitride^	58	**27.3**
metal-organic framework	127	20.8	g-C_3N_4 nanosheets^	58	22.9
photocatalysis*	123	**26.0**	graphitic carbon nitride^	58	23.5
g-C_3N_4^	103	22.6	N-doped carbon^	58	22.5

Note: Contextually related terms are marked by the symbols * and **. Nitrogen-related terms are marked by the symbol ^.

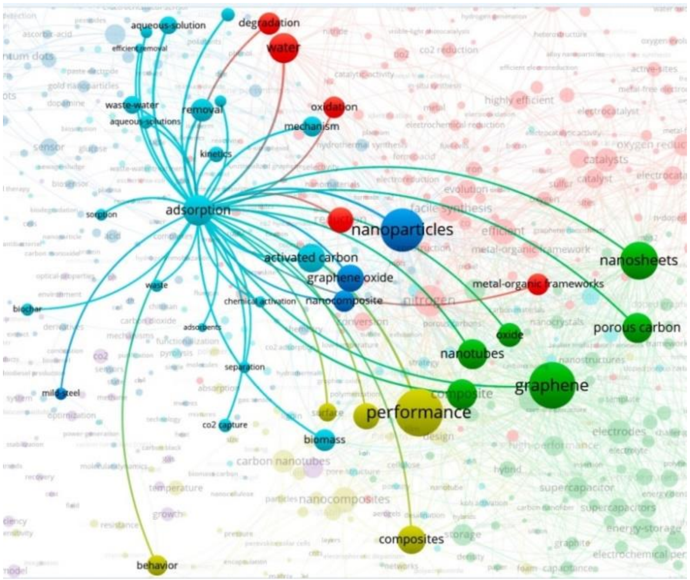

Fig. 13. Cluster 6. The main links of the term "adsorption" with the other terms

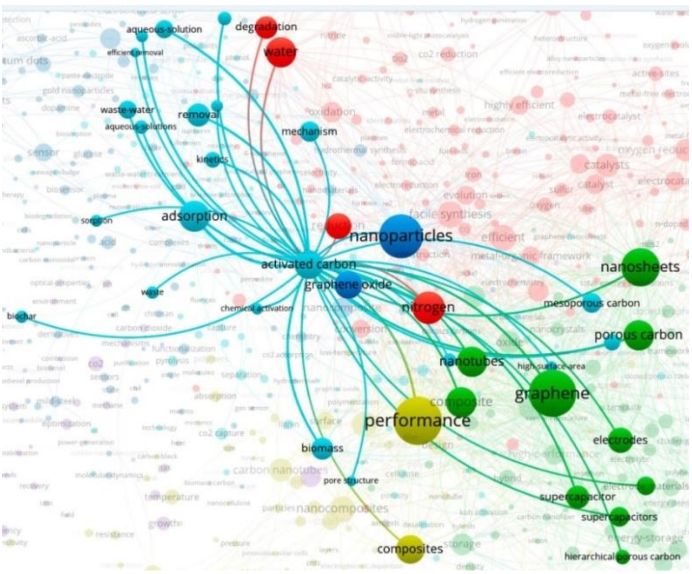

Fig. 14. Cluster 6. The main links of the term "activated carbon" with the other terms

This cluster is represented by the publications [38–43].

The conditional name of this cluster is “Adsorption and organic pollutants”. Corresponding keywords: adsorption, activated carbon, mesoporous carbon, adsorbent, separation, sorption, chemical activation, high-surface-area, biomass, organic pollutants, waste-water treatment.

Conclusions

1. The brief bibliometric analysis of scientific publications on “Carbon” topic indicated a high level of applied research in the following Web of Science categories: Materials Science (Ceramics, Composites); Physical Chemistry; Condensed Matter Physics; Polymer Science; Nanoscience and Nanotechnology; Metallurgy and Metallurgical Engineering; Energy and Fuels. This knowledge can provide a foundation for the development of technology and the production of carbon-based materials.
2. The wide involvement of the world’s leading economies in research on this topic was revealed. The good positions of Russia and the Russian Academy of Sciences in the research on carbon-based materials, the importance of the fuel and energy sector for the economy and the necessity of its transformation to achieve the United Nations Sustainable Development Goals make the subject of combining the tasks of hydrogen energy and carbon-based materials production relevant for applied and fundamental science.
3. The clustering method based on the co-occurrence of keywords yielded the six areas of research, which can be conventionally labelled as:

1) catalysis, hydrogen-production, nitrogen-doped carbon;

2) graphite/graphene-based energy storage systems;

3) sensors and emissions based on carbon quantum dots;

4) nanocomposites and their physical properties;

5) energy consumption and climate change;

6) adsorption and organic pollutants.

The topic of hydrogen energy is well traced in the studies related to carbon-based materials.

The research area of hydrogen and graphite co-production is highly relevant, since it combines the needs of hydrogen energy development, graphite-based materials production (particularly for renewable energy purposes) and the objectives of CO_2 emission reduction [44–50].

Especially important are the studies on the production of hydrogen by thermochemical pyrolysis of CH_4 using a carbon catalyst and solar energy, which produces hydrogen and black carbon without generating CO_2 [51–52].

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References

1. *Staffell I., Scamman D., Velazquez Abad A.* et al. The role of hydrogen and fuel cells in the global energy system // Energy & Environmental Science. 2019. Vol. 12, No. 2. P. 463–491. https://doi.org/10.1039/c8ee01157e

2. The future of hydrogen. Report prepared by the IEA for the G20, Japan. 2019. 203 p. https://www.iea.org/reports/the-future-of-hydrogen (Accessed on 27.05.2021).

3. The hydrogen economy – a path towards low carbon development. SKOLKOVO Energy Centre, Moscow School of Management SKOLKOVO. 2019. 62 p. https://energy.skolkovo.ru/downloads/documents/SEneC/Research/SKOLKOVO_EneC_Hydrogen-economy_Eng.pdf (Accessed on 27.05.2021).

4. *van Eck N.J., Waltman L.* Software survey: VOSviewer, a computer program for bibliometric mapping // Scientometrics. 2010. Vol. 84, No. 2. P. 523–538. https://doi.org/10.1007/s11192-009-0146-3

5. *Perianes-Rodriguez A., Waltman L., van Eck N.J.* Constructing bibliometric networks: a comparison between full and fractional counting // Journal of Informetrics. 2016. Vol. 10, No. 4. P. 1178–1195. https://doi.org/10.1016/j.joi.2016.10.006

6. *Zhu J., Hu L., Zhao P.* et al. Recent advances in electrocatalytic hydrogen evolution using nanoparticles // Chemical Reviews. 2020. Vol. 120, No. 2. P. 851–918. https://doi.org/10.1021/acs.chemrev.9b00248

7. *Abdelhamid H.N.* A review on hydrogen generation from the hydrolysis of sodium borohydride // International Journal of Hydrogen Energy. 2021. Vol. 46, No, 1. P. 726–765. https://doi.org/10.1016/j.ijhydene.2020.09.186

8. *Cao S., Low J., Yu J., Jaroniec M.* Polymeric Photocatalysts Based on Graphitic Carbon Nitride // Advanced Materials. 2015. Vol. 27, No. 13. P. 2150–2176. https://doi.org/10.1002/adma.201500033

9. *Ong W.-J., Tan L.-L., Ng Y.H.* et al. Graphitic carbon nitride (g-C_3N_4)-based photocatalysts for artificial photosynthesis and environmental remediation: are we a step closer to achieving sustainability? // Chemical Reviews. 2016. Vol. 116, No. 12. P. 7159–7329. https://doi.org/10.1021/acs.chemrev.6b00075

10. *Orooji Y., Ghanbari M., Amiri O., Salavati-Niasari M.* Facile fabrication of silver iodide/graphitic carbon nitride nanocomposites by notable photo-catalytic performance through sunlight and antimicrobial activity // Journal of Hazardous Materials. 2020. Vol. 389. P. 122079. https://doi.org/10.1016/j.jhazmat.2020.122079

11. *Wang Q., Domen K.* Particulate photocatalysts for light-driven water splitting: mechanisms, challenges, and design strategies // Chemical Reviews. 2020. Vol. 120, No. 2. P. 919–985. https://doi.org/10.1021/acs.chemrev.9b00201

12. *Li Z., Ji S., Liu Y., Cao X.* et al. Well-Defined materials for heterogeneous catalysis: from nanoparticles to isolated single-atom sites // Chemical Reviews. 2020. Vol. 120, No. 2. P. 623–682. https://doi.org/10.1021/acs.chemrev.9b00311

13. *Liu P., Gao S., Wang Y., Huang Y.* et al. Carbon nanocages with N-doped carbon inner shell and Co/N-doped carbon outer shell as electromagnetic wave absorption materials //Chemical Engineering Journal. 2020. Vol. 381. P. 122653. https://doi.org/10.1016/j.cej.2019.122653

14. *Wang H., Maiyalagan T., Wang X.* Review on recent progress in nitrogen-doped graphene: synthesis, characterization, and its potential applications // ACS Catalysis. 2012. Vol. 2, No. 5. P. 781–794. https://doi.org/10.1021/cs200652y

15. *Wang Y., Ding B., Guo D. et al.* A novel way to synthesize nitrogen and oxygen co-doped porous carbon for high performance supercapacitors // Microporous and Mesoporous Materials. 2019. Vol. 282. P. 114–120. https://doi.org/10.1016/j.micromeso.2019.03.031

16. *Abdel Maksoud, M.I.A., Fahim, R.A., Shalan, A.E.* et al. Advanced materials and technologies for supercapacitors used in energy conversion and storage: a review // Environmental Chemistry Letters. 2020. Vol. 19, No. 1. P. 375–439. https://doi.org/10.1007/s10311-020-01075-w

17. *Pandolfo A.G., Hollenkamp A.F.* Carbon properties and their role in supercapacitors // Journal of Power Sources. 2006. Vol. 157, No. 1. P. 11–27. https://doi.org/10.1016/j.jpowsour.2006.02.065

18. *Yuan C., Wu H.B., Xie Y., Lou X.W.D.* Mixed transition-metal oxides: design, synthesis, and energy-related applications // Angewandte Chemie International Edition. 2014. Vol. 53, No. 6. P. 1488–1504. https://doi.org/10.1002/anie.201303971

19. *Zhang L.L., Zhao X.S.* Carbon-based materials as supercapacitor electrodes // Chemical Society Reviews. 2009. Vol. 38, No. 9. P. 2520–2531. https://doi.org/10.1039/b813846j

20. *Korkmaz S., Kariper I.A.* Graphene and graphene oxide based aerogels: Synthesis, characteristics and supercapacitor applications // Journal of Energy Storage. 2020. Vol. 27. P. 101038. https://doi.org/10.1016/j.est.2019.101038

21. *Li H., Liang J.* Recent development of printed micro-supercapacitors: printable materials, printing technologies, and perspectives // Advanced Materials. 2020. Vol. 32, No. 3. P. 1805864. https://doi.org/10.1002/adma.201805864

22. *Ahmadian-Fard-Fini S., Ghanbari D., Amiri O., Salavati-Niasari M.* Electro-spinning of cellulose acetate nanofibers/Fe/carbon dot as photoluminescence sensor for mercury (II) and lead (II) ions // Carbohydrate Polymers. 2020. Vol. 229. P. 115428. https://doi.org/10.1016/j.carbpol.2019.115428

23. *Qiao G., Liu L., Hao X.* et al. Signal transduction from small particles: sulfur nanodots featuring mercury sensing, cell entry mechanism and in vitro tracking performance // Chemical Engineering Journal. 2020. Vol. 382. P. 122907. https://doi.org/10.1016/j.cej.2019.122907

24. *Shen J., Zhu Y., Yang X.* et al. Graphene quantum dots: emergent nanolights for bioimaging, sensors, catalysis and photovoltaic devices // Chemical Communications. 2012. Vol. 48, No. 31. P. 3686–3699. https://doi.org/10.1039/c2cc00110a

25. *Wang Y., Hu A.* Carbon quantum dots: synthesis, properties and applications // Journal of Materials Chemistry C. 2014. Vol. 2, No. 34. P. 6921–6939. https://doi.org/10.1039/c4tc00988f

26. *Wu S., Min H., Shi W., Cheng P.* Multicenter metal-organic framework-based ratiometric fluorescent sensors // Advanced Materials. 2020. Vol. 32, No. 3. P. 1805871. https://doi.org/10.1002/adma.201805871

27. *Zhu S., Meng Q., Wang L.* et al. Highly photoluminescent carbon dots for multicolor patterning, sensors, and bioimaging // Angewandte Chemie International Edition. 2013. Vol. 52, No. 14. P. 3953–3957. https://doi.org/10.1002/anie.201300519

28. *Huang Z.-M., Zhang Y.-Z., Kotaki M., Ramakrishna S.* A review on polymer nanofibers by electrospinning and their applications in nanocomposites // Composites Science and Technology. 2003. Vol. 63, No. 15. P.2223–2253. https://doi.org/10.1016/S0266-3538(03)00178-7

29. *Liang C., Qiu H., Song P.* et al. Ultra-light MXene aerogel/wood-derived porous carbon composites with wall-like “mortar/brick” structures for electromagnetic interference shielding //Science Bulletin. 2020. Vol. 65, No. 8. P. 616–622. https://doi.org/10.1016/j.scib.2020.02.009

30. *Thostenson E.T., Ren Z.F., Chou T.W.* Advances in the science and technology of carbon nanotubes and their composites: a review // Composites Science and Technology. 2001. Vol. 61, No. 13. P.1899–1912. https://doi.org/10.1016/S0266-3538(01)00094-X

31. *Wei H., Wang H., Li A.* et al. Multifunctions of polymer nanocomposites: environmental remediation, electromagnetic interference shielding, and sensing applications // ChemNanoMat. 2020. Vol. 6, No. 2. P. 174–184. https://doi.org/10.1002/cnma.201900588

32. *Wong E.W., Sheehan P.E., Lieber C.M.* Nanobeam mechanics: elasticity, strength, and toughness of nanorods and nanotubes // Science. 1997. Vol. 277, No. 5334. P. 1971–1975. https://doi.org/10.1126/science.277.5334.1971

33. *Arouri M.E.H., Ben Youssef A., M’henni H., Rault C.* Energy consumption, economic growth and CO_2 emissions in Middle East and North African countries // Energy Policy. 2012. Vol. 45. P. 342–349. https://doi.org/10.1016/j.enpol.2012.02.042

34. *Holmberg K., Andersson P., Erdemir A.* Global energy consumption due to friction in passenger cars // Tribology International. 2012. Vol. 47. P. 221–234. https://doi.org/10.1016/j.triboint.2011.11.022

35. *Iram R., Zhang J., Erdogan S.* et al. Economics of energy and environmental efficiency: evidence from OECD countries // Environmental Science and Pollution Research. 2020. Vol. 27, No. 4. P. 3858–3870. https://doi.org/10.1007/s11356-019-07020-x

36. *Jalil A., Mahmud S.F.* Environment Kuznets curve for CO_2 emissions: a cointegration analysis for China // Energy Policy. 2009. Vol. 37, No. 12. P. 5167–5172. https://doi.org/10.1016/j.enpol.2009.07.044

37. *Liu M., Ren X., Cheng C., Wang Z.* The role of globalization in CO_2 emissions: a semi-parametric panel data analysis for G7 // Science of the Total Environment. 2020. Vol. 718. P. 137379. https://doi.org/10.1016/j.scitotenv.2020.137379

38. *Tang L., Yang G.-D., Zeng G.-M.* et al. Synergistic effect of iron doped ordered mesoporous carbon on adsorption-coupled reduction of hexavalent chromium and the relative mechanism study // Chemical Engineering Journal. 2014. Vol. 239. P. 114–122. https://doi.org/10.1016/j.cej.2013.10.104

39. *Zbair M., Bottlinger M., Ainassaari K.* et al. Hydrothermal carbonization of argan nut shell: functional mesoporous carbon with excellent performance in the adsorption of bisphenol a and diuron // Waste Biomass Valorization. 2020. Vol. 11, No. 4. P. 1565–1584. https://doi.org/10.1007/s12649-018-00554-0

40. *Chen M., Guo C., Hou S.* et al. A novel Z-scheme AgBr/P-g-C_3N_4 heterojunction photocatalyst: excellent photocatalytic performance and photocatalytic mechanism for ephedrine degradation // Applied Catalysis B: Environmental. 2020. Vol. 266. https://doi.org/10.1016/j.apcatb.2020.118614

41. *Dou M., Wang J., Gao B.* et al. Photocatalytic difference of amoxicillin and cefotaxime under visible light by mesoporous g-C_3N_4: mechanism, degradation pathway and DFT calculation // Chemical Engineering Journal. 2020. Vol. 383. P. 123134. https://doi.org/10.1016/j.cej.2019.123134

42. *Rezakazemi M., Ebadi Amooghin A., Montazer-Rahmati M.M.* et al. State-of-the-art membrane based CO_2 separation using mixed matrix membranes (MMMs): an overview on current status and future directions // Progress in Polymer Science. 2014. Vol. 39, No. 5. P. 817–861. https://doi.org/10.1016/j.progpolymsci.2014.01.003

43. *Zhou C., Lai C., Huang D.* et al. Highly porous carbon nitride by supramolecular preassembly of monomers for photocatalytic removal of sulfamethazine under visible light driven // Applied Catalysis B: Environment. 2018. Vol. 220. P. 202–210. https://doi.org/10.1016/j.apcatb.2017.08.055

44. *Dalapati G.K., Masudy-Panah S., Moakhar R.S.* et al. Nanoengineered advanced materials for enabling hydrogen economy: functionalized graphene–incorporated cupric oxide catalyst for efficient solar hydrogen production // Global Challenges. 2020. Vol. 4, No. 3. P. 1900087. https://doi.org/10.1002/gch2.201900087

45. *Donphai W., Phichairatanaphong O., Klysubun W., Chareonpanich M.* Hydrogen and carbon allotrope production through methane cracking over Ni/bimodal porous silica catalyst: effect of nickel precursor // International Journal of Hydrogen Energy. 2018. P. 21798–21809. https://doi.org/10.1016/j.ijhydene.2018.10.049

46. *Han K.-S., Kim J.-H., Kim H.-K., Hwang K.-T.* Direct methane cracking using a mixed conducting ceramic membrane for production of hydrogen and carbon // International Journal of Hydrogen Energy. 2013. Vol. 38, No. 36. P.16133–16139. https://doi.org/10.1016/j.ijhydene.2013.10.027

47. *Musamali R., Isa Y.M.* Decomposition of methane to carbon and hydrogen: a catalytic perspective // Energy Technology. 2019. Vol. 7, No. 6. P. 1800593. https://doi.org/10.1002/ente.201800593

48. *Sun C., Zheng X., Bai B.* Hydrogen purification using nanoporous graphene membranes and its economic analysis // Chemical Engineering Science. 2019. Vol. 208. P. 115141. https://doi.org/10.1016/j.ces.2019.07.059

49. *Takenaka S., Shigeta Y., Tanabe E., Otsuka K.* Methane decomposition into hydrogen and carbon nanofibers over supported Pd-Ni catalysts: Characterization of the catalysts during the reaction // Journal of Physical Chemistry B. 2004. Vol. 108, No. 23. P. 7656–7664. https://doi.org/10.1021/jp0377331

50. *Tozzini V., Pellegrini V.* Prospects for hydrogen storage in graphene // Physical Chemistry Chemical Physics. 2013. Vol. 15, No. 1. P. 80–89. https://doi.org/10.1039/c2cp42538f

51. *Boretti A.* There are hydrogen production pathways with better than green hydrogen economic and environmental costs // International Journal of Hydrogen Energy. 2021. Vol. 46, No. 6. P. 23988–23995. https://doi.org/10.1016/j.ijhydene.2021.04.182

52. *Sánchez-Bastardo N., Schlögl R., Ruland H*. Methane pyrolysis for zero-emission hydrogen production: A potential bridge technology from fossil fuels to a renewable and sustainable hydrogen economy // Industrial & Engineering Chemistry Research. 2021. Vol. 60, No. 32. P. 11855–11881. https://doi.org/10.1021/acs.iecr.1c01679

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Краткий библиометрический анализ публикаций Web of Science по теме «Углерод» за 2019–2020 гг.

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Аннотация. Дан краткий библиометрический анализ 5000 наиболее цитируемых научных публикаций, представленных в базе Web of Science по теме «Углерод» за 2019–2020 гг. Показано, что в исследования по данной тематике вовлечены ведущие мировые научные центры Китая, США, Индии, Южной Кореи, Японии, Германии, а также Российская академия наук. Доминировали следующие направления научных исследований: материаловедение, физическая химия, нанотехнологии, инженерная химия, прикладная физика, энергетика, электрохимия, экология, физика конденсированного состояния.

Методом кластеризации на основе совместной встречаемости ключевых слов авторов и системы Web of Science выявлено шесть направлений исследований: 1. катализ, получение водорода, углеродные материалы, легированные азотом; 2. накопители энергии на основе графита/графена; 3. сенсоры и излучатели на основе углеродных квантовых точек; 4. нанокомпозиты и их физические свойства; 5. потребление энергии и изменение климата; 6. адсорбция и органические загрязнители.

Выдвинуто предположение о перспективности исследований по совместному производству водорода и графита, которые могут объединить интересы развития водородной энергетики и производства новых материалов.

Ключевые слова: библиометрический анализ, Web of Science, наукометрия, углерод, графен, водород, катализ, нанокомпозиты, накопители энергии.

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Литература

1. *Staffell I., Scamman D., Velazquez Abad A.* et al. The role of hydrogen and fuel cells in the global energy system // Energy & Environmental Science. 2019. Vol. 12, No. 2. P. 463–491. https://doi.org/10.1039/c8ee01157e

2. The future of hydrogen. Report prepared by the IEA for the G20, Japan. 2019. 203 p. https://www.iea.org/reports/the-future-of-hydrogen (Дата обращения 27.05.2021).

3. The hydrogen economy – a path towards low carbon development. SKOLKOVO Energy Centre, Moscow School of Management SKOLKOVO. 2019. 62 p. https://energy.skolkovo.ru/downloads/documents/SEneC/Research/SKOLKOVO_EneC_Hydrogen-economy_Eng.pdf (Дата обращения 27.05.2021).

4. *van Eck N.J., Waltman L.* Software survey: VOSviewer, a computer program for bibliometric mapping // Scientometrics. 2010. Vol. 84, No. 2. P. 523–538. https://doi.org/10.1007/s11192-009-0146-3

5. *Perianes-Rodriguez A., Waltman L., van Eck N.J.* Constructing bibliometric networks: a comparison between full and fractional counting // Journal of Informetrics. 2016. Vol. 10, No. 4. P. 1178–1195. https://doi.org/10.1016/j.joi.2016.10.006

6. *Zhu J., Hu L., Zhao P.* et al. Recent advances in electrocatalytic hydrogen evolution using nanoparticles // Chemical Reviews. 2020. Vol. 120, No. 2. P. 851–918. https://doi.org/10.1021/acs.chemrev.9b00248

7. *Abdelhamid H.N.* A review on hydrogen generation from the hydrolysis of sodium borohydride // International Journal of Hydrogen Energy. 2021. Vol. 46, No, 1. P. 726–765. https://doi.org/10.1016/j.ijhydene.2020.09.186

8. *Cao S., Low J., Yu J., Jaroniec M.* Polymeric Photocatalysts Based on Graphitic Carbon Nitride // Advanced Materials. 2015. Vol. 27, No. 13. P. 2150–2176. https://doi.org/10.1002/adma.201500033

9. *Ong W.-J., Tan L.-L., Ng Y.H.* et al. Graphitic carbon nitride (g-C_3N_4)-based photocatalysts for artificial photosynthesis and environmental remediation: are we a step closer to achieving sustainability? // Chemical Reviews. 2016. Vol. 116, No. 12. P. 7159–7329. https://doi.org/10.1021/acs.chemrev.6b00075

10. *Orooji Y., Ghanbari M., Amiri O., Salavati-Niasari M.* Facile fabrication of silver iodide/graphitic carbon nitride nanocomposites by notable photo-catalytic performance through sunlight and antimicrobial activity // Journal of Hazardous Materials. 2020. Vol. 389. P. 122079. https://doi.org/10.1016/j.jhazmat.2020.122079

11. *Wang Q., Domen K.* Particulate photocatalysts for light-driven water splitting: mechanisms, challenges, and design strategies // Chemical Reviews. 2020. Vol. 120, No. 2. P. 919–985. https://doi.org/10.1021/acs.chemrev.9b00201

12. *Li Z., Ji S., Liu Y., Cao X.* et al. Well-Defined materials for heterogeneous catalysis: from nanoparticles to isolated single-atom sites // Chemical Reviews. 2020. Vol. 120, No. 2. P. 623–682. https://doi.org/10.1021/acs.chemrev.9b00311

13. *Liu P., Gao S., Wang Y., Huang Y.* et al. Carbon nanocages with N-doped carbon inner shell and Co/N-doped carbon outer shell as electromagnetic wave absorption materials // Chemical Engineering Journal. 2020. Vol. 381. P. 122653. https://doi.org/10.1016/j.cej.2019.122653

14. *Wang H., Maiyalagan T., Wang X.* Review on recent progress in nitrogen-doped graphene: synthesis, characterization, and its potential applications // ACS Catalysis. 2012. Vol. 2, No. 5. P. 781–794. https://doi.org/10.1021/cs200652y

15. *Wang Y., Ding B., Guo D., et al.* A novel way to synthesize nitrogen and oxygen co-doped porous carbon for high performance supercapacitors // Microporous and Mesoporous Materials. 2019. Vol. 282. P. 114–120. https://doi.org/10.1016/j.micromeso.2019.03.031

16. *Abdel Maksoud, M.I.A., Fahim, R.A., Shalan, A.E.* et al. Advanced materials and technologies for supercapacitors used in energy conversion and storage: a review // Environmental Chemistry Letters. 2020. Vol. 19, No. 1. P. 375–439. https://doi.org/10.1007/s10311-020-01075-w

17. *Pandolfo A.G., Hollenkamp A.F.* Carbon properties and their role in supercapacitors // Journal of Power Sources. 2006. Vol. 157, No. 1. P. 11–27. https://doi.org/10.1016/j.jpowsour.2006.02.065

18. *Yuan C., Wu H.B., Xie Y., Lou X.W.D.* Mixed transition-metal oxides: design, synthesis, and energy-related applications // Angewandte Chemie International Edition. 2014. Vol. 53, No. 6. P. 1488–1504. https://doi.org/10.1002/anie.201303971

19. *Zhang L.L., Zhao X.S.* Carbon-based materials as supercapacitor electrodes // Chemical Society Reviews. 2009. Vol. 38, No. 9. P. 2520–2531. https://doi.org/10.1039/b813846j

20. *Korkmaz S., Kariper I.A.* Graphene and graphene oxide based aerogels: Synthesis, characteristics and supercapacitor applications // Journal of Energy Storage. 2020. Vol. 27. P. 101038. https://doi.org/10.1016/j.est.2019.101038

21. *Li H., Liang J.* Recent development of printed micro-supercapacitors: printable materials, printing technologies, and perspectives // Advanced Materials. 2020. Vol. 32, No. 3. P. 1805864. https://doi.org/10.1002/adma.201805864

22. *Ahmadian-Fard-Fini S., Ghanbari D., Amiri O., Salavati-Niasari M.* Electro-spinning of cellulose acetate nanofibers/Fe/carbon dot as photoluminescence sensor for mercury (II) and lead (II) ions // Carbohydrate Polymers. 2020. Vol. 229. P. 115428. https://doi.org/10.1016/j.carbpol.2019.115428

23. *Qiao G., Liu L., Hao X.* et al. Signal transduction from small particles: sulfur nanodots featuring mercury sensing, cell entry mechanism and in vitro tracking performance // Chemical Engineering Journal. 2020. Vol. 382. P. 122907. https://doi.org/10.1016/j.cej.2019.122907

24. *Shen J., Zhu Y., Yang X.* et al. Graphene quantum dots: emergent nanolights for bioimaging, sensors, catalysis and photovoltaic devices // Chemical Communications. 2012. Vol. 48, No. 31. P. 3686–3699. https://doi.org/10.1039/c2cc00110a

25. *Wang Y., Hu A.* Carbon quantum dots: synthesis, properties and applications // Journal of Materials Chemistry C. 2014. Vol. 2, No. 34. P. 6921–6939. https://doi.org/10.1039/c4tc00988f

26. *Wu S., Min H., Shi W., Cheng P.* Multicenter metal-organic framework-based ratiometric fluorescent sensors // Advanced Materials. 2020. Vol. 32, No. 3. P. 1805871. https://doi.org/10.1002/adma.201805871

27. *Zhu S., Meng Q., Wang L.* et al. Highly photoluminescent carbon dots for multicolor patterning, sensors, and bioimaging // Angewandte Chemie International Edition. 2013. Vol. 52, No. 14. P. 3953–3957. https://doi.org/10.1002/anie.201300519

28. *Huang Z.-M., Zhang Y.-Z., Kotaki M., Ramakrishna S.* A review on polymer nanofibers by electrospinning and their applications in nanocomposites // Composites Science and Technology. 2003. Vol. 63, No. 15. P.2223–2253. https://doi.org/10.1016/S0266-3538(03)00178-7

29. *Liang C., Qiu H., Song P.* et al. Ultra-light MXene aerogel/wood-derived porous carbon composites with wall-like “mortar/brick” structures for electromagnetic interference shielding // Science Bulletin. 2020. Vol. 65, No. 8. P. 616–622. https://doi.org/10.1016/j.scib.2020.02.009

30. *Thostenson E.T., Ren Z.F., Chou T.W.* Advances in the science and technology of carbon nanotubes and their composites: a review // Composites Science and Technology. 2001. Vol. 61, No. 13. P.1899–1912. https://doi.org/10.1016/S0266-3538(01)00094-X

31. *Wei H., Wang H., Li A.* et al. Multifunctions of polymer nanocomposites: environmental remediation, electromagnetic interference shielding, and sensing applications // ChemNanoMat. 2020. Vol. 6, No. 2. P. 174–184. https://doi.org/10.1002/cnma.201900588

32. *Wong E.W., Sheehan P.E., Lieber C.M.* Nanobeam mechanics: elasticity, strength, and toughness of nanorods and nanotubes // Science. 1997. Vol. 277, No. 5334. P. 1971–1975. https://doi.org/10.1126/science.277.5334.1971

33. *Arouri M.E.H., Ben Youssef A., M’henni H., Rault C.* Energy consumption, economic growth and CO_2 emissions in Middle East and North African countries // Energy Policy. 2012. Vol. 45. P. 342–349. https://doi.org/10.1016/j.enpol.2012.02.042

34. *Holmberg K., Andersson P., Erdemir A.* Global energy consumption due to friction in passenger cars // Tribology International. 2012. Vol. 47. P. 221–234. https://doi.org/10.1016/j.triboint.2011.11.022

35. *Iram R., Zhang J., Erdogan S.* et al. Economics of energy and environmental efficiency: evidence from OECD countries // Environmental Science and Pollution Research. 2020. Vol. 27, No. 4. P. 3858–3870. https://doi.org/10.1007/s11356-019-07020-x

36. *Jalil A., Mahmud S.F.* Environment Kuznets curve for CO_2 emissions: a cointegration analysis for China // Energy Policy. 2009. Vol. 37, No. 12. P. 5167–5172. https://doi.org/10.1016/j.enpol.2009.07.044

37. *Liu M., Ren X., Cheng C., Wang Z.* The role of globalization in CO_2 emissions: a semi-parametric panel data analysis for G7 // Science of the Total Environment. 2020. Vol. 718. P. 137379. https://doi.org/10.1016/j.scitotenv.2020.137379

38. *Tang L., Yang G.-D., Zeng G.-M.* et al. Synergistic effect of iron doped ordered mesoporous carbon on adsorption-coupled reduction of hexavalent chromium and the relative mechanism study // Chemical Engineering Journal. 2014. Vol. 239. P. 114–122. https://doi.org/10.1016/j.cej.2013.10.104

39. *Zbair M., Bottlinger M., Ainassaari K.* et al. Hydrothermal carbonization of argan nut shell: functional mesoporous carbon with excellent performance in the adsorption of bisphenol a and diuron // Waste Biomass Valorization. 2020. Vol. 11, No. 4. P. 1565–1584. https://doi.org/10.1007/s12649-018-00554-0

40. *Chen M., Guo C., Hou S.* et al. A novel Z-scheme AgBr/P-g-C_3N_4 heterojunction photocatalyst: excellent photocatalytic performance and photocatalytic mechanism for ephedrine degradation // Applied Catalysis B: Environmental. 2020. Vol. 266. https://doi.org/10.1016/j.apcatb.2020.118614

41. *Dou M., Wang J., Gao B.* et al. Photocatalytic difference of amoxicillin and cefotaxime under visible light by mesoporous g-C_3N_4: mechanism, degradation pathway and DFT calculation // Chemical Engineering Journal. 2020. Vol. 383. P. 123134. https://doi.org/10.1016/j.cej.2019.123134

42. *Rezakazemi M., Ebadi Amooghin A., Montazer-Rahmati M.M.* et al. State-of-the-art membrane based CO_2 separation using mixed matrix membranes (MMMs): an overview on current status and future directions // Progress in Polymer Science. 2014. Vol. 39, No. 5. P. 817–861. https://doi.org/10.1016/j.progpolymsci.2014.01.003

43. *Zhou C., Lai C., Huang D.* et al. Highly porous carbon nitride by supramolecular preassembly of monomers for photocatalytic removal of sulfamethazine under visible light driven // Applied Catalysis B: Environment. 2018. Vol. 220. P. 202–210. https://doi.org/10.1016/j.apcatb.2017.08.055

44. *Dalapati G.K., Masudy-Panah S., Moakhar R.S.* et al. Nanoengineered advanced materials for enabling hydrogen economy: functionalized graphene–incorporated cupric oxide catalyst for efficient solar hydrogen production // Global Challenges. 2020. Vol. 4, No. 3. P. 1900087. https://doi.org/10.1002/gch2.201900087

45. *Donphai W., Phichairatanaphong O., Klysubun W., Chareonpanich M.* Hydrogen and carbon allotrope production through methane cracking over Ni/bimodal porous silica catalyst: effect of nickel precursor // International Journal of Hydrogen Energy. 2018. P. 21798–21809. https://doi.org/10.1016/j.ijhydene.2018.10.049

46. *Han K.-S., Kim J.-H., Kim H.-K., Hwang K.-T.* Direct methane cracking using a mixed conducting ceramic membrane for production of hydrogen and carbon // International Journal of Hydrogen Energy. 2013. Vol. 38, No. 36. P.16133–16139. https://doi.org/10.1016/j.ijhydene.2013.10.027

47. *Musamali R., Isa Y.M.* Decomposition of methane to carbon and hydrogen: a catalytic perspective // Energy Technology. 2019. Vol. 7, No. 6. P. 1800593. https://doi.org/10.1002/ente.201800593

48. *Sun C., Zheng X., Bai B.* Hydrogen purification using nanoporous graphene membranes and its economic analysis // Chemical Engineering Science. 2019. Vol. 208. P. 115141. https://doi.org/10.1016/j.ces.2019.07.059

49. *Takenaka S., Shigeta Y., Tanabe E., Otsuka K.* Methane decomposition into hydrogen and carbon nanofibers over supported Pd-Ni catalysts: Characterization of the catalysts during the reaction // Journal of Physical Chemistry B. 2004. Vol. 108, No. 23. P. 7656–7664. https://doi.org/10.1021/jp0377331

50. *Tozzini V., Pellegrini V.* Prospects for hydrogen storage in graphene // Physical Chemistry Chemical Physics. 2013. Vol. 15, No. 1. P. 80–89. https://doi.org/10.1039/c2cp42538f

51. *Boretti A.* There are hydrogen production pathways with better than green hydrogen economic and environmental costs // International Journal of Hydrogen Energy. 2021. Vol. 46, No. 6. P. 23988–23995. https://doi.org/10.1016/j.ijhydene.2021.04.182

52. *Sánchez-Bastardo N., Schlögl R., Ruland H*. Methane pyrolysis for zero-emission hydrogen production: A potential bridge technology from fossil fuels to a renewable and sustainable hydrogen economy // Industrial & Engineering Chemistry Research. 2021. Vol. 60, No. 32. P. 11855–11881. https://doi.org/10.1021/acs.iecr.1c01679