Hot Topics in Material Science☆

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In this, the first of two special reports, science writers Maria Burke and Jon Evans provide their insights into the hottest research topics in materials science by looking through the publication data provided by Scopus and SciVal.

Introduction

Materials science is a truly interdisciplinary field, encompassing researchers from physics, chemistry, biology, mathematics, computer science and engineering. Together, these researchers search for new materials, study their structure and properties, develop novel synthesis and processing technologies, and engineer the materials for commercial applications. These applications range from laptop batteries to drug capsules, from composites for aircraft to coatings for ships, from plastics for prosthetics to smart textiles, showing that materials research reaches into all corners of the modern world.

That reach is only going to become more extensive, as materials research is increasingly called upon to solve some of the most pressing challenges facing mankind: switching from fossil fuels to renewable sources of energy, creating a truly connected world through the 'internet of things', treating currently intractable diseases. These will all benefit from advances in materials research, from improved battery materials to nanoscale computer processing materials to targeted drug delivery materials.

In this new report, *Hot Topics in Material Science*, the authors derive insights into the current state and future prospects of materials research, by drawing on data provided by Scopus and SciVal, part of Elsevier's research intelligence suite. The report covers eight classes of materials: biomedical; ceramics; drug-related materials; energy materials; electronic, optical and magnetic (EOM) materials; metals and alloys; nanomaterials; and polymers and plastics. For each material class, the authors use the wealth of data provided by Scopus and SciVal to uncover trends in research activity. They identify the topics and technologies within each material class that are receiving most interest from researchers, and the countries producing the largest volume of research and the most influential research, which is very often not the same. They also reveal how this has changed over the past few years. To investigate commercial interest in these research activities, they also looked at industrial collaborations and patent citations. All this analysis is backed up by a host of informative tables and graphs.

Finally, they bring all these analyses together to provide a snapshot of the current state of materials research, revealing which are the 'hottest' topics. To add expert opinion, they also conducted interviews with the editors-in-chief of some of Elsevier's high-impact materials journals, who gave their personal views on the current state of materials research and its future development.

Report methodology

The information in this report was generated by conducting searches in SciVal on each of the eight material classes for the years 2012 to 2016. These years were chosen to highlight recent developments in 2D materials and also to ensure that comparisons were between comprehensive data sets comprising whole years.

Throughout, this report refers to specialist terms and metrics used by Scopus and SciVal to collate and analyze the research data. These terms and metrics are defined below.

Scholarly output

A collective term for a range of academic publications, including journal articles, conference proceedings, and book chapters. A search in SciVal will reveal all the scholarly outputs relating to

☆ A summary of this report has been published as *The wonderful world of materials: Perspectives on the materials research landscape*. Mater. Today, Volume 22, January–February 2019, Pages 1-2.

the specific search term produced over a set time period. Each scholarly output comes with its associated metadata, including title, abstract, authors and their affiliated institutions, number of views and citations, and associated patent citations, allowing for a range of detailed analyses.

Keyphrases

Concepts that appear frequently in the titles and abstracts of the scholarly outputs, as determined by automated text mining. Keyphrases indicate active research topics in each material class and can be displayed as keyphrase maps. Here, the size of each keyphrase relates to its frequency, with larger keyphrases being more frequent, and the color of the keyphrase indicates whether its appearance in the scholarly outputs is increasing or decreasing, with red increasing and blue decreasing.

Field-weighted citation impact (FWCI)

The ratio of citations received relative to the expected world average for the subject field, publication type and publication year. Together with the percentage of scholarly outputs published in the top 5% of journals, it is used in this report as an indication of the overall impact of a country's research.

Patent-citations count

The total count of patents citing the scholarly output for each material class, based on patent information from the European Patent Office, the US Patent Office, the UK Intellectual Property Office, the Japan Patent Office and the World Intellectual Property Organization.

Focus on materials

Biomedical materials

Biomedical materials are designed to repair or replace damaged, diseased or missing tissues or organs in the body, and comprise living cells growing on artificial scaffolds. Conventionally, this occurs within the body, with the scaffold providing a framework on which new cells grow to fix the damage, such as a small hole in the heart of a new-born baby. But scientists are also exploring growing cells on scaffolds in the laboratory to produce tissues and even whole organs that can be used to test drugs or implanted into patients. Often this involves growing stem cells, which can differentiate into many different types of bodily cells in response to specific chemical cues.

Between 2012 and 2016, 73,532 scholarly outputs were produced on biomedical materials, reflecting overall growth of 15%. The five keyphrases that appeared most in these outputs were: tissue engineering, stem cells, medical imaging, tissue scaffolds and optical tomography (a form of medical imaging) (see Figure 1).

This indicates that the challenge of growing living cells on synthetic materials has been the most active area of research over this period, as tissue engineering and stem cells appeared most frequently. The number of articles mentioning tissue engineering fell slightly over this time, from 972 in 2012 to 924 in 2016, while the number mentioning stem cells grew by 5%, from 735 in 2012 to 775 in 2016. Several high-growth keyphrases were also cell-related, including cell engineering (590%) and cytology (169%), which means the study of the structure and function of cells.

In contrast, research into scaffold materials appeared to slow down, with the number of outputs mentioning tissue scaffolds declining by 69%, from 740 in 2012 to 228 in 2016, although mentions of the related keyphrase scaffolds (biology) did increase. Mentions of some scaffold materials, including hydrogels and nanofibers, also decreased, although mentions of graphene increased by 163%.

Researchers in the US produced the largest number of scholarly outputs on biomedical materials between 2012 and 2016 (19,956), but Chinese researchers are catching up fast with 16,052; over this time, China's scholarly output grew by 49%, while US output grew by just 6% (see Table 1).

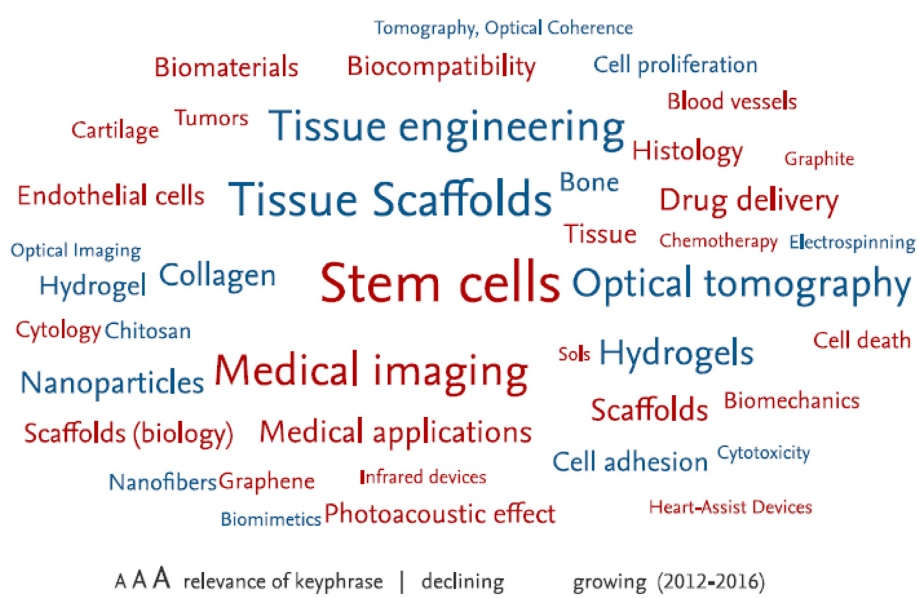

FIGURE 1

Keyphrase map for biomedical materials.

TABLE 1

Top 5 country producers of scholarly output for biomedical materials.

	Scholarly Output per year				
Country	**2012**	**2013**	**2014**	**2015**	**2016**
China	2562	2624	3529	3511	3826
Germany	1155	1094	1182	1199	1079
Japan	877	895	909	867	824
United Kingdom	787	816	888	969	859
United States	3842	3884	4078	4093	4059

A fairly high proportion of China's scholarly output is high impact, with an overall FWCI of 1.79 and 26% published in the top 5% of journals (compared to 1.56 and 23% for US researchers). Other countries producing high-impact research include Singapore (2.58 and 43%), Hong Kong (2.20 and 38%) and South Korea (1.61 and 30%).

When it comes to academic/industry collaborations, however, China is at 1%, while the US is at 3%. Countries with the largest proportion of academic/industry collaborations include the Netherlands (7%), Switzerland (6%), Germany (5%), the UK (4%) and South Korea (3%). Overall, 3364 patents cited the scholarly outputs on biomedical materials between 2012 and 2016, with each 1000 scholarly outputs on biomedical materials receiving an average of 45.7 patent citations.

Ceramics

Ceramics are inorganic, non-metallic, solid materials comprising metal, non-metal, or metalloid atoms primarily held in ionic and covalent bonds. Long used for pottery, ceramics have steadily become more advanced, with scientists developing ceramics with exceptional properties that make them highly resistant to melting, bending, stretching, corrosion or wear. As a result, they are increasingly being used as substitutes for plastics and metals in numerous high-performance applications such as replacement bone, electronic devices and engines. Examples of advanced ceramic materials include alumina, zirconia, silicon nitride and silicon carbide. One class of copper-based ceramic, known as cuprate, is even showing great potential as a high-temperature superconductor.

Between 2012 and 2016, 70,526 scholarly outputs were produced on ceramics, reflecting overall growth of 10%. The five keyphrases that appeared most in these outputs were: ceramic materials, sintering, dielectric properties, glass ceramics and solid-state reactions (see Figure 2).

As four of these keyphrases relate to ceramic materials or methods for producing ceramics, they indicate that the development of novel ceramic materials remains a highly active area of research. However, whereas the keyphrases ceramic materials and solid-state reaction saw steady growth in their usage (37% and 21% respectively), sintering and glass ceramics experienced little or no growth.

Several keyphrases relating to the unusual electric properties of certain ceramics experienced growth from 2012 to 2016. These included ferroelectricity (23%), in which the electric polarization of the ceramic material changes on application of an external electric field, and piezoelectricity (31%), in which mechanical stress applied to the material generates electricity and vice versa. Ferroelectric materials are being developed as novel capacitors and computer memory, while piezoelectric materials are used as sensors, actuators and in analytical instruments.

Chinese researchers are significantly ahead of other countries in terms of scholarly output on ceramics (21,818), generating

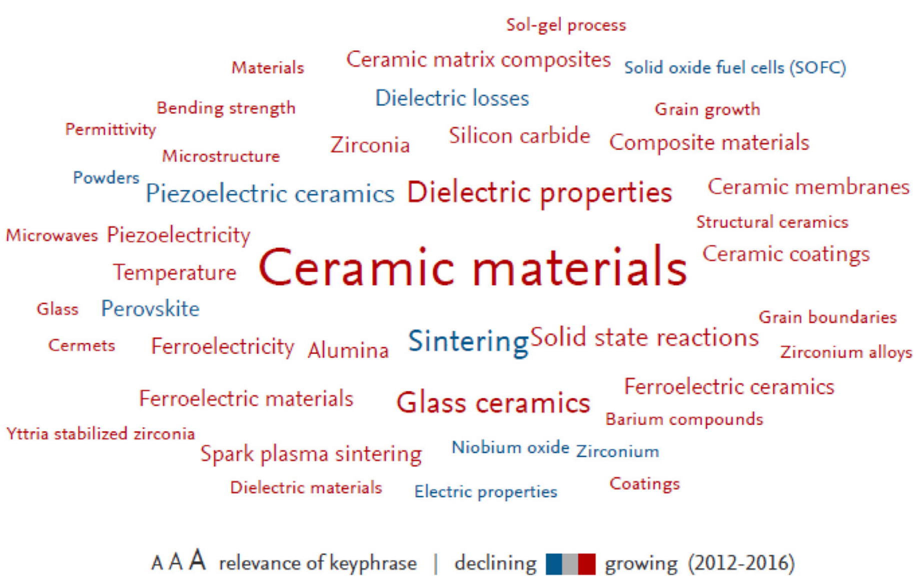

FIGURE 2

Keyphrase map for ceramics.

TABLE 2

Top 5 country producers of scholarly output for ceramics.

Country	Scholarly Output per year				
	2012	2013	2014	2015	2016
China	3970	3854	4505	4799	4690
Germany	888	885	925	905	895
India	726	905	952	963	959
Japan	832	1003	945	794	808
United States	1656	1710	1749	1649	1619

more than double the output of US researchers (8383), who were in second place (see Table 2).

China also experienced steady growth in scholarly output between 2012 and 2016 (18%), while India's output increased even more (32%), but the other countries in the top five saw very little change in activity.

In terms of research impact, China and India both rank below the other countries in the top five, especially the US. China's scholarly output has a FWCI of 0.75 and 7% of its output appeared in the top 5% of journals, while for India the figures are 0.82 and 5%, compared with 1.29 and 17% for the US. Other countries producing high impact research on ceramics include Switzerland (1.70 and 23%), Australia (1.44 and 22%) and the UK (1.38 and 20%).

China and India also rank lower on academic/industry collaborations, which account for less than 1% of their scholarly output, compared with the US, where they account for 4%. Countries with the largest proportion of academic/industry collaborations include France (7%), Japan (5%) and the UK (4%). Overall, 801 patents cited the scholarly outputs on ceramics between 2012 and 2016, with each 1000 scholarly outputs on ceramics receiving an average of 11.4 patent citations.

Drug-related materials

Drug-related materials is a diverse and expanding class, covering substances used to deliver medicines and therapies. Nanotechnology is opening up new avenues for drug delivery vehicles, allowing drug release to be controlled and targeted to specific areas of the body, which means lower doses and reduced side-effects. Various nanostructures, including dendrimers, liposomes, polymers, and nanotubes, are being tested as carriers in drug delivery systems, particularly for treating and detecting cancer.

Between 2012 and 2016, 25,949 scholarly outputs were produced on drug-related materials, reflecting overall growth of 52%. The five keyphrases that appeared most in these outputs were: drug delivery, nanoparticles, biocompatibility, hydrogels, and micelles (see Figure 3).

Drug delivery was the top keyphrase by some way, but it has significant overlap with three of the other top five keyphrases, as nanoparticles, hydrogels, and micelles are all under development as drug delivery systems. Hydrogels are attractive as they have several properties in common with human tissue, while the hydrophobic interior of polymer micelles can house drugs that are poorly soluble in aqueous solution. Exactly how these materials interact with the body determines clinical success, which helps to explain why the keyphrase biocompatibility grew by 157% over the period.

The development of novel drug delivery vehicles for treating cancer is a particularly active area of research, as shown by sharp rises in the appearance of cancer-related keyphrases such as cytology (377%), oncology (149%), chemotherapy (124%) and

FIGURE 3

Keyphrase map for drug materials.

TABLE 3

Top 5 country producers of scholarly output for drug materials.

Country	Scholarly Outputs per year 2012	2013	2014	2015	2016
China	1086	1328	1568	1722	1893
Germany	186	203	240	286	278
India	341	426	515	517	652
South Korea	226	240	279	284	295
United States	851	921	1061	1110	1254

tumors (106%). Researchers are using nanoparticles, micelles, and liposomes to deliver chemotherapy drugs directly to tumors, thereby helping to prevent these highly toxic compounds from damaging healthy cells. They are also using certain metal nanoparticles, including gold nanoparticles, to first reveal tumors and then kill them through heating, by taking advantage of their ability to scatter and absorb light.

China was the main producer of scholarly output on drug-related materials (7597) between 2012 and 2016, followed by the US (5197), India (2451), South Korea (1324), and Germany (1993) (see Table 3).

China saw a substantial increase in its scholarly output over this period (74%), as did India (91%), whereas Germany (49%), the US (47%) and South Korea (31%) all experienced more modest growth, perhaps reflecting the more mature state of drug material research in these countries.

India's research had the lowest average impact of the top five, with a FWCI of 1.37 and 26% of its output appearing in the top 5% of journals, whereas the US had the highest, with a FWCI of 2.13 and 53% appearing the top 5%, closely followed by China (2.05 and 44%). Other countries producing high-impact research on drug-related materials include Singapore (2.51 and 57%), the Netherlands (2.13 and 50%), Switzerland (2.09 and 50%) and the UK (2.02 and 47%).

Countries with the largest proportion of academic/industry collaborations include the Netherlands (7%), Switzerland (7%), the UK (5%) and Germany (4%). Overall, 1462 patents cited the scholarly outputs on drug-related materials between 2012 and 2016, with each 1000 scholarly outputs on drug-related materials receiving an average of 56.3 patent citations.

Electronic, optical, and magnetic materials

Electronic, optical, and magnetic (EOM) materials encompass a wide range of substances, including semiconductors and light-responsive materials. These are used to create complex systems, such as integrated electronic circuits, optoelectronic devices, and magnetic and optical mass storage media.

Between 2012 and 2016, 448,312 scholarly outputs were produced on EOM materials, reflecting overall growth of 9%. Lasers is the keyphrase that appeared most frequently over this period (33,872), but its usage has remained steady, with hardly any growth (see Figure 4). Lasers are often used to help synthesize and characterize novel EOM materials such as ceramic nanocomposites or novel semiconductors.

The other keyphrases in the top five have achieved much greater rates of growth; they are photonics (78%), optical fibers (47%), graphene (43%), and solar cells (19%). Photonics – the technology of generating, controlling, and detecting light – involves materials such as semiconductors, metamaterials, plasmonic materials, and light-emitting materials. These go into

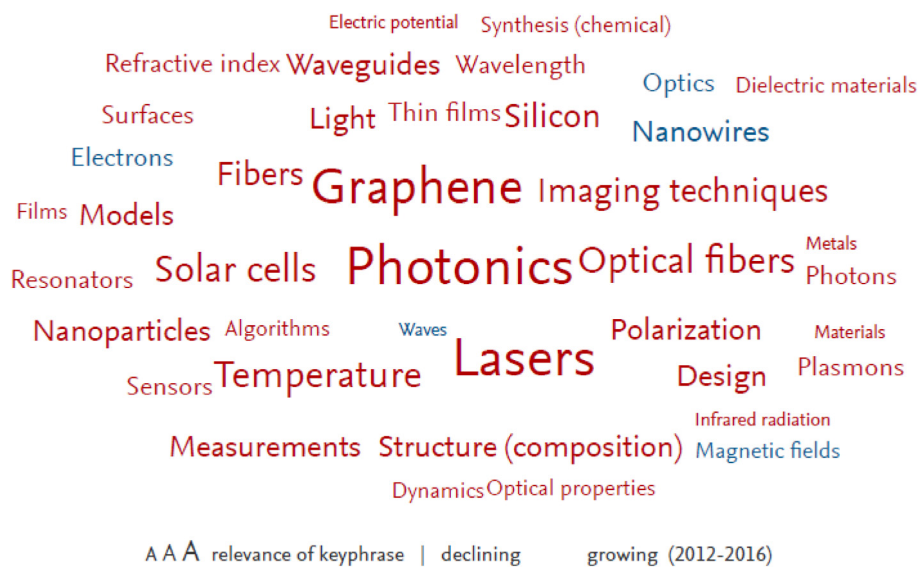

FIGURE 4

Keyphrase map for EOM materials.

TABLE 4

Top 5 country producers of scholarly output for EOM materials.

Country	Scholarly Output per year 2012	2013	2014	2015	2016
China	18,719	21,629	24,967	26,073	24,716
France	4725	4274	4983	4679	4322
Germany	6741	6253	7604	6910	5965
Japan	6522	6760	6955	6434	5851
United States	18,137	17,237	19,736	18,412	16,174

components like optical modulators, photodetectors, wavelength-division multiplexing filters and switches.

The rise of photonics is being driven by ongoing interest in solar cells and optical fibers, which are also in the top five keyphrases, but also by the development of optical computing, in which digital information is encoded in flashes of light, offering the promise of faster computing speeds. Other keyphrases related to optical computing also saw growth, including waveguides (21%) and metamaterials (27%).

The traditional way to increase computer speeds has been to reduce the size of transistors and other electronic components, but this is becoming harder. To keep reducing their scale, researchers are turning to nanomaterials, which explains the growth in keyphrases such as graphene and nanoparticles. Rather interestingly, the keyphrase that has seen the largest jump in use is infrared devices (203%), which include thermal imaging cameras, detectors (of carbon dioxide and pollutants, for example), and wireless communication devices such as TV remotes and cordless keyboards.

China was the largest producer of scholarly outputs over the period (116,104), followed by the US (89,696), Germany (33,473), Japan (32,522), and France (22,983) (see Table 4). China saw its scholarly output grow by 32% between 2012 and 2016, although it fell from a high in 2015, whereas the outputs of the other four countries all fell slightly, with the US falling by 11%.

All the top five countries produced research with a similar impact: the percentage of their scholarly output in the top 5% of journals varied between 7% and 9%, and the FWCI varied between 1.17 and 1.39 for four of the countries, with China slightly lower at 0.89. Several countries produced research with a higher impact, including Australia (15% and 1.49), Singapore (15% and 1.44), the UK (15% and 1.35), Switzerland (11% and 1.68), and the Netherlands (10.1% and 1.84).

The countries conducting the highest proportion of collaborations with industry were the Netherlands (10%), Sweden (8%), Switzerland (7%), Japan (7%), and South Korea (7%) Overall, 7724 patents cited the scholarly outputs on EOM materials between 2012 and 2016, with each 1000 scholarly outputs on EOM materials receiving an average of 17.2 patent citations.

Energy materials

As the world shifts from fossil fuels to renewable and sustainable energy technologies, researchers are designing materials to support these new technologies: Not only solar cell materials and electrode materials for use in fuel cells, but also novel materials for storing energy, especially novel battery materials. These are required to produce better batteries for a growing range of applications, including electric vehicles. They're also needed because many sources of renewable energy, such as solar and wind, are intermittent, producing abundant energy when it is sunny or windy, but none at all when it is dark or calm.

Between 2012 and 2016, 55,452 scholarly outputs were produced on energy materials, reflecting overall growth of 54%. The five keyphrases that appeared most in these outputs were: materials, energy storage, graphene, x-ray spectroscopy, and lithium alloys (see Figure 5).

Although by far the most popular keyphrase, appearing in 43,564 scholarly outputs between 2012 and 2016, is materials, it is clearly too broad a keyphrase to provide much insight into this field. However, not only is energy storage the second most popular keyphrase, appearing in 4256 scholarly outputs, but two of the other top five scholarly outputs – graphene and lithium alloys – both relate to energy storage. With its high-surface area, graphene is being investigated as an electrode material for batteries, while scientists are developing novel lithium alloys to try to enhance the charging speed and storage capacity of lithium-ion batteries. All three keyphrases also saw rapid growth in their use over the period, with energy storage growing by 215%, graphene growing by 174% and lithium alloys growing by a highly impressive 917%.

Many other keyphrases relating to energy storage experienced rapid growth, including electric batteries (5275%), lithium compounds (512%), secondary batteries (775%) and electrodes (233%). Several keyphrases relating to solar cells also experienced growth, with the largest being perovskite (224%), a crystalline light-absorbing material that is receiving a great deal of attention as a cheaper, more efficient alternative to the silicon in conventional solar cells. Scientists are also actively exploring the structure and properties of these novel energy materials, as shown by the fact that X-ray spectroscopy was in the top five keyphrases and other analytical keyphrases such as energy dispersive spectroscopy and binding energy experienced healthy growth.

China (14,589) and the US (11,630) were the two largest producers of scholarly output on energy materials between 2012 and 2016, followed some way behind by Germany (3927), India (3738), and South Korea (3111) (see Table 5). China's growth in scholarly output over the period, at 130%, far exceeds that of the other countries in the top five, although India experienced healthy growth of 90%. Of the top five countries, the US produced the research with the highest impact, with a FWCI of 2.2 and 33% of its scholarly output appearing in the top 5% of journals, followed by China, with 1.8 and 26%. Other countries producing high-impact research on energy materials include Sin-

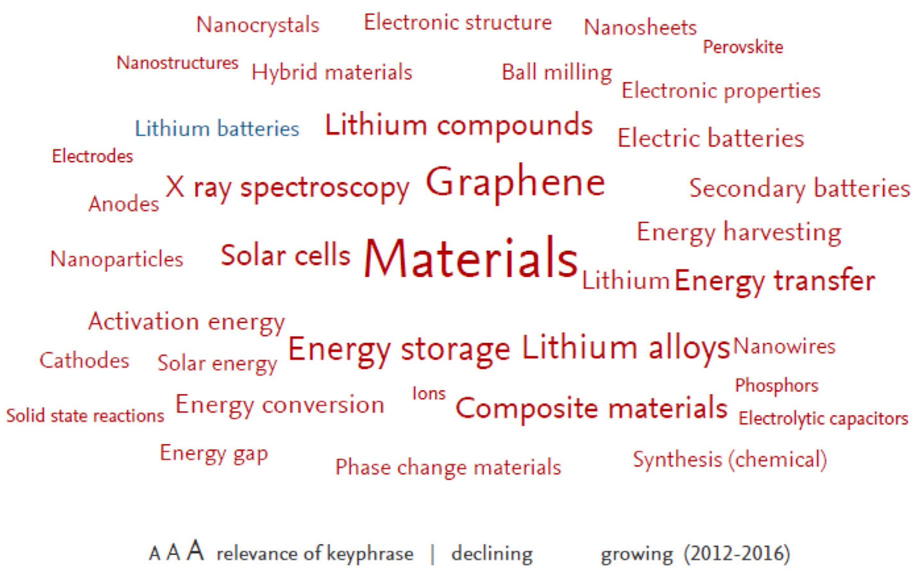

FIGURE 5

Keyphrase map for energy materials.

TABLE 5

Top 5 country producers of scholarly output for energy materials.

Country	Scholarly Output per year 2012	2013	2014	2015	2016
China	1775	2155	2882	3686	4091
Germany	705	690	781	916	835
India	511	615	686	956	970
South Korea	469	549	640	723	730
United States	1979	2075	2382	2628	2566

gapore (3.51 and 51%), Switzerland (2.46 and 34%), Saudi Arabia (2.24 and 28%), and the Netherlands (2.09 and 33%).

When it comes to collaborating with industry, the Netherlands sits top of the table (9%) followed by Switzerland (8%), Japan (6%) and France (6%). Overall, 1302 patents cited the scholarly outputs on energy materials between 2012 and 2016, with each 1000 scholarly outputs on energy materials receiving an average of 23.5 patent citations.

Metals and alloys

Pure metals may possess useful properties such as good electrical conductivity or hardness, but adding other elements, including different metals, can produce alloys that possess a whole range of additional properties, such as the ability to withstand high temperatures.

The properties of new alloys are often difficult to calculate. Both physical and mechanical properties are mainly governed by the microstructure of the alloy, which describes how different crystalline structures within the alloy are arranged and fit together. That's why much research effort is focused on determining and modifying this microstructure.

Nevertheless, by taking advantage of their growing understanding of alloys and the latest computer modeling, scientists are increasingly developing advanced alloys with enhanced strength and robustness. They are also moving beyond traditional alloys, which contain only one or two other elements as minor components, to so-called high-entropy alloys, which contain four or more different elements in similar proportions and can possess even more impressive properties.

Between 2012 and 2016, 151,557 scholarly outputs were produced on metals and alloys, reflecting overall growth of 11%. The top five keyphrases were microstructure, alloys, steel, mechanical properties, and synthesis (chemical), all of which experienced similar levels of growth over this period, between 15% and 28% (see Figure 6).

Of all the keyphrases in metals and alloys, graphene saw the fastest growth over this period, at 153%, which seems to be due to scientists exploring the potential of combining graphene with metals in various ways. These include coating metals with graphene to prevent corrosion, producing composites of graphene and metal as novel electrode materials and doping graphene with metal to confer catalytic ability.

After graphene came nickel as a keyphrase, which grew by 73%, reflecting how widely this metal and its alloys are now being used. Nickel-based alloys are known for their resistance to corrosion and heat, and so are used in aircraft gas turbines, steam turbine power plants and nuclear power systems. Nickel is also an important component of shape memory alloys, which return to their previously defined shape when heated. Other keyphrases that experienced significant growth include slags (59%), magnesium (53%), corrosion (53%) and powder metallurgy

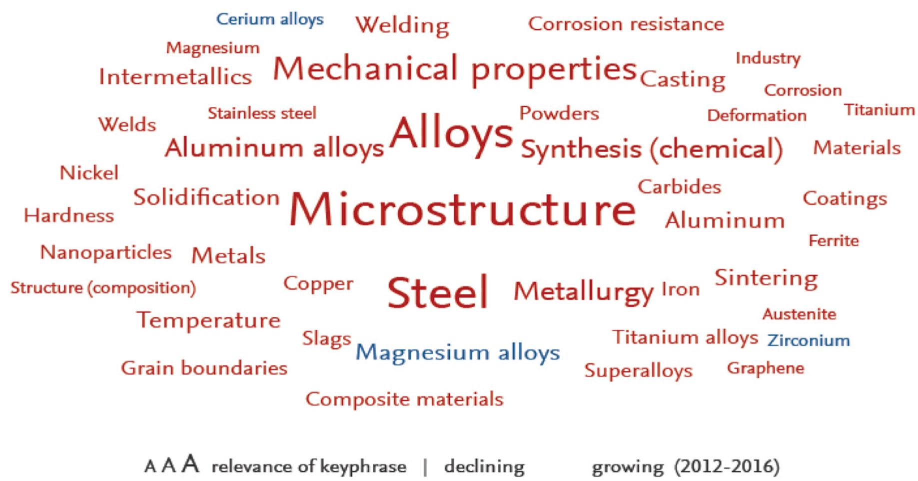

FIGURE 6

Keyphrase map for metals and alloys.

TABLE 6

Top 5 country producers of scholarly output for metals and alloys.

Country	Scholarly Output per year 2012	2013	2014	2015	2016
China	9174	10,526	11,734	13,333	11,908
Germany	1761	1614	1853	1846	1631
India	1003	1251	1540	1676	1949
Japan	2183	2024	2185	2120	1854
United States	2737	2653	2981	3034	2790

(49%), while cerium alloys and zirconium both experienced major declines, by 96% and 61% respectively.

China was by far the largest producer of scholarly outputs on metals and alloys between 2012 and 2016, with 56,675, followed by the US (14,195), Japan (10,366), Germany (8705), and India (7419) (see Table 6).

Although China experienced healthy growth in its output over this period, at 30%, India's output actually grew much faster, at 94%. In contrast, US output barely grew at all, while that of Germany and Japan both declined slightly.

Of the top five countries, the US produced the highest impact research, with a FWCI of 1.51 and 40% of its output in the top 5% of journals, while China's research had the lowest impact, with 1.02 and 18%. Other countries producing high-impact research include Singapore (2.11 and 54%), Switzerland (1.74 and 50%), Spain (1.44 and 48%), and the UK (1.66 and 45%).

Japan is the stand-out country for collaborations with industry, at 9%, followed by Sweden (8%), Austria (7%), South Korea (7%) and the UK (7%), whereas the figures for China and the US were 2% and 5% respectively. Overall, 2109 patents cited the scholarly outputs on metals and alloys between 2012 and 2016, with each 1000 scholarly outputs on metals and alloys receiving an average of 13.9 patent citations.

Nanomaterials

Nanomaterials describe structures between 1 nanometer (nm) and 100 nm in size. Due to their tiny proportions, nanomaterials have a comparatively large surface area and are also subject to quantum effects, which gives them properties such as catalysis and fluorescence that aren't found in the same materials at larger scales.

They come in numerous different forms. These include nanoparticles made from metals such gold, silver and titanium dioxide with various different shapes, including spheres and rods, and nano-sized polymers known as dendrimers. There are also carbon-based nanomaterials, such as carbon nanotubes and graphene, which is also an example of an atom-thick, two-dimensional material, and semiconductor crystals known as quantum dots. Already, nanomaterials are found in catalysts, smart textiles, drug delivery systems, surface coatings for electronic devices and cosmetics, and are continuously being developed for new applications.

Between 2012 and 2016, 27,559 scholarly outputs were produced on nanomaterials, reflecting overall growth of 65%. The top five keyphrases were nanostructured materials, nanoparticles, nanostructures, graphene and nanotechnology (see Figure 7).

The number of outputs mentioning nanostructured materials, at 19,619, far exceeded the other keyphrases, and this keyphrase also saw growth of 68%. This was far lower than graphene, however, which saw growth of 194%. Indeed, many of the nanomaterial keyphrases saw their usage more than double between 2012 and 2016. These keyphrases encompassed specific types of nanomaterials, such as nanosheets (199%), nanotubes

FEATURE COMMENT

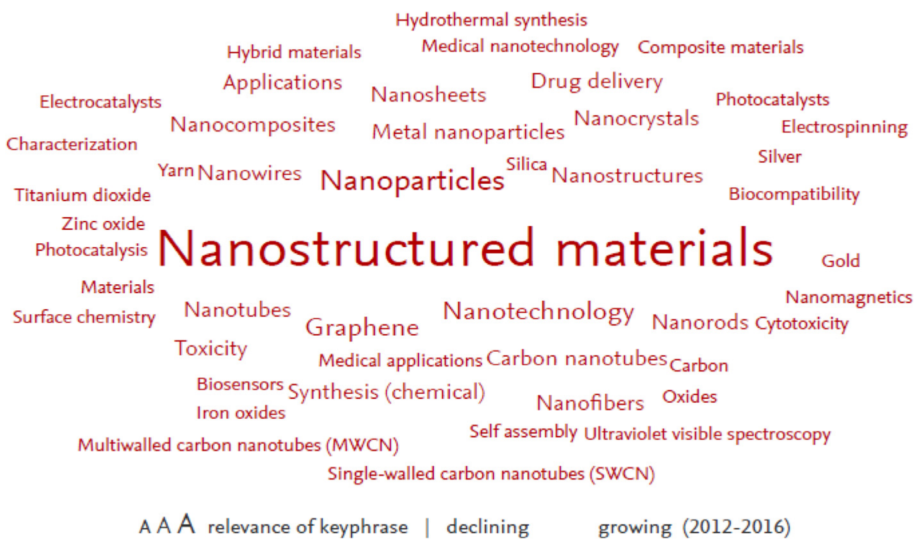

FIGURE 7

Keyphrase map for nanomaterials.

(127%) and metal nanoparticles (163%), elements commonly used in nanomaterials such as carbon (152%) and silver (106%), and techniques for analyzing nanomaterials such as transmission electron microscopy (627%). All of which confirm that nanomaterials remain a highly active research area.

The keyphrase that experienced the largest growth – an astonishing 9960% – was yarns. This reflects the fact that scientists are looking to incorporate nanomaterials into textiles to repel water, reduce wrinkles, eliminate static, and introduce electrical conductivity and other 'smart' properties. For example, researchers are 'twist-spinning' carbon nanotubes into yarns to produce fibers that can store and generate energy.

China produced far more scholarly outputs on nanomaterials (7841) than any other country between 2012 and 2016, with its output growing by 88% over this time (see Table 7).

The US was second with 6312 scholarly outputs, but it experienced much slower growth, at 33%. Indeed, the two countries produced practically the same number of scholarly outputs in 2012, but by 2016 China's output was higher by more than 600. India was third and saw the highest growth, at 113%, followed by South Korea and Germany.

With a FWCI of 1.93 and 34% of its scholarly outputs appearing in the top 5% of journals, China's nanomaterials research had a higher impact than India's or South Korea's, but not that of the US (2.2 and 43%) or Germany (2.15 and 40%). Other countries producing high-impact nanomaterial research include Australia (2.81 and 46%), the Netherlands (2.71 and 44%), Sweden (2.45 and 35%) and Hong Kong (2.41 and 42%).

The Netherlands leads the pack in the number of collaborations its researchers have with industry (12%), followed by Switzerland (9%), the UK (7%), Sweden (6%) and Germany (6%). For both China and the US, the figures are lower, at 1% and 3% respectively. Overall, 711 patents cited the scholarly outputs on nanomaterials between 2012 and 2016, with each 1000 scholarly outputs on nanomaterials receiving an average of 25.8 patent citations.

Polymers and plastics

Polymers can be natural materials like rubber or cellulose or synthetic materials like polyethylene and polystyrene and can possess a wide range of different properties, from soft and stretchy to hard and tough, but they are all made up of chains of monomers.

Thermoplastic polymers, which melt when heated, then harden again when cooled, account for around four-fifths of synthetic polymer production. The rest are thermosets, which are 'set' permanently once formed and can't be melted. Polyethylene (containers and bags), polypropylene (rope, bottles, yarns, nonwoven fabrics), polystyrene (packaging) and polyvinyl chloride (PVC; construction materials, fabrics) are all thermoplastics. Thermosets include epoxy resins (glues, adhesives), polyur-

TABLE 7

Top 5 country producers of scholarly output for nanomaterials.

Country	Scholarly Output per year				
	2012	2013	2014	2015	2016
China	1087	1336	1569	1807	2042
Germany	177	212	257	268	297
India	297	383	455	513	634
South Korea	208	241	288	327	337
United States	1071	1201	1234	1382	1424

ethanes (plastic foams for thermal insulation and upholstery), and silicones (lubricants, medical implants).

Even though polymers are a mature sector, scientists are still busy developing new polymers and enhancing the properties of existing polymers to expand their range of applications. For example, to reduce weight, automobile and aircraft manufacturers want polymers that are tough enough to replace sections and components currently made from metal.

Between 2012 and 2016, 114,249 scholarly outputs were produced on polymers, reflecting overall growth of 13%. The top five keyphrases were polymers, block copolymers, polypropylenes, hydrogels, and acrylic monomers (see Figure 8).

Block copolymers, which comprise two or more different polymer materials linked by covalent bonds, offer an effective way to produce polymers with novel properties, which explains why it was the most popular keyphrase after polymers. However, it experienced no overall growth between 2012 and 2016. Hydrogels, comprising a network of water-absorbent polymer chains, experienced the most growth, with 38%, perhaps because they are a comparatively novel polymer material.

The keyphrase showing the highest growth in activity was chains (5850%), which represent a vital area of study as researchers seek to develop ever stronger and more flexible polymers. The physical properties of polymers depend on chain length, and on their degree of branching and cross-linking.

On the other hand, thermoplastics saw a dip in mentions over the period (−47%), as did some individual thermoplastics such as polypropylenes (−9%). This perhaps reflects a shift in research toward novel polymers such as hydrogels and elastomers (127%), and natural polymers such as cellulose (36%). Reinforced plastics also saw an increase (55%), as did materials increasingly used to reinforce plastics, including nanoparticles (41%) and nanofibers (40%), which would include carbon fibers and nanotubes.

Researchers in China produced significantly more scholarly outputs on polymers than any other country between 2012 and 2016, with 31,280 (see Table 8).

The US was second, with 16,983, but actually experienced higher growth in scholarly output than China (44% vs 14%), with a big jump in 2016. The other three countries in the top 5 – Germany, India, and Japan – experienced little or no growth.

Of the top five, the US and Germany produced the research with the highest impact: the US had a FWCI of 1.35 and 28% of its scholarly output appeared in the top 5% of journals, while Germany had a FWCI of 1.2 and 22% of its output appeared in the top 5%. For China, the figures were 0.91 and 9%. Other countries producing high-impact polymer research include Australia (1.8 and 26%), Belgium (1.67 and 29%), Sweden (1.58 and 22%) and the UK (1.48 and 26%).

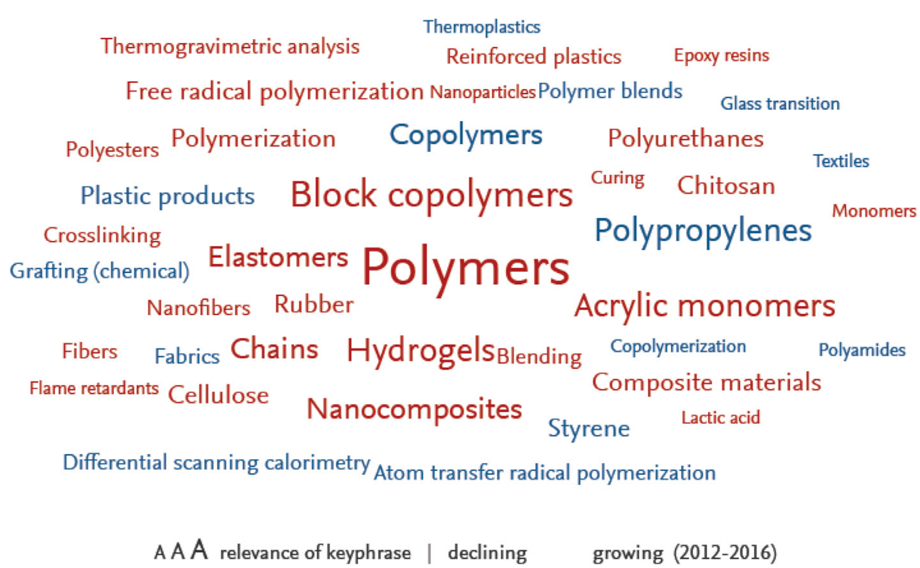

FIGURE 8

Keyphrase map for polymers and plastics.

TABLE 8

Top 5 country producers of scholarly output for polymers and plastics.

	Scholarly Output per year				
Country	**2012**	**2013**	**2014**	**2015**	**2016**
China	5815	6179	6441	6224	6621
Germany	1531	1594	1648	1652	1714
India	1300	1298	1285	1278	1539
Japan	1474	1512	1378	1444	1398
United States	2957	3200	3222	3336	4268

Researchers from the Netherlands are pursuing many more collaborations with industry (21%), compared with China (1%) and the US (5%). Generally, European countries seem much more active in this area, including Switzerland (10%), Belgium (6%), Germany (6%), and the UK (6%). Overall, 2893 patents cited the scholarly outputs on polymers and plastics between 2012 and 2016, with each 1000 scholarly outputs on polymers and plastics receiving an average of 25.3 patent citations.

Material advances

According to the data from SciVal, scholarly outputs for nanomaterials, energy materials and drug-related materials are growing significantly faster than the other five material classes. But the total number of scholarly outputs for nanomaterials, energy materials, and drug-related materials is significantly lower than for these other five classes (see Table 9). This suggests that part of the reason for the slower growth in biomedical materials, polymers and plastics, metals and alloys, ceramics, and EOM materials is simply because they are more mature, rather than due to a lack of research activity.

According to the editors of some of Elsevier's materials science journals, energy materials is perhaps the single hottest topic in material science at the moment.

> "One of the areas that I think is becoming really interesting for researchers is energy materials, in terms of designing better energy storage and energy conversion systems," says Jun Lou, professor of materials science and nanoengineering at Rice University, US, and co-editor-in-chief of Materials Today. "That would include electrode materials and electrolytes in batteries, supercapacitors and fuel cells, and more recently we've seen a surge in perovskite solar cells."

> "There is a lot of focus now on material for energy harvesting and storage," agrees Gleb Yushin, a professor in the School of Materials and Engineering at the Georgia Institute of Technology, US, and co-editor-in-chief of Materials Today.

Energy materials experienced the second largest growth in scholarly outputs between 2012 and 2016, at 54%, with energy storage the second most popular energy material keyphrase (after materials). Supporting Lou's comments, energy material keyphrases relating to batteries, capacitors and perovskite solar cells all experienced rapid growth, including electric batteries (5275%) and lithium alloys (917%), electrolytic capacitors (425%), and perovskite (224%).

TABLE 9

Scholarly output 2012–2016 for each material class.

Material class	Scholarly output	% growth (2012–2016)
Nanomaterials	27,559	65
Energy materials	55,452	54
Drug materials	25,949	52
Biomedical materials	73,532	15
Polymers and plastics	114,249	13
Metals and alloys	151,557	11
Ceramics	70,526	10
EOM materials	448,312	9

Reflecting the current dominance of lithium-ion batteries, several of the energy materials keyphrases related to lithium, including lithium, lithium compounds, and lithium alloys, all of which experienced growth. Many keyphrases, including anodes, electrodes, nanosheets, and manganese oxide, related to the development of novel materials for batteries, which are being developed both to improve lithium-ion batteries and to develop novel battery technologies. According to Robert Hurt, professor of engineering at Brown University, US, and former editor-in-chief of *Carbon*, more and more research effort is now looking beyond conventional lithium-ion batteries to novel technologies such as lithium-air and sodium.

Nanomaterials experienced the largest growth in scholarly output between 2012 and 2016, at 65%. According to Yushin, researchers are currently investigating a broad range of nano-sized and nanostructured materials, made from various substances, including metals, ceramics, and polymers, and with a wide range of properties. This diversity is reflected in the variety of nanomaterials keyphrases, which include substances such as silver, gold, carbon, zinc oxide, and titanium dioxide, and types of nanomaterials such as nanoparticles, nanotubes, nanowires, nanorods, nanocrystals, and nanosheets. All these keyphrases experienced growth between 2012 and 2016.

Another major nanomaterial keyphrase is graphene, which was the fourth most popular nanomaterial keyphrase and saw growth of 194% between 2012 and 2016. But graphene isn't just restricted to nanomaterials; in fact, it is the single most prevalent keyphrase, appearing in four other material classes – biomaterials, EOM materials, energy materials, and metals and alloys.

This shows the range of applications that graphene, with its impressive strength and conductivity, is now being developed for. These include as a physical support for growing cells, as an electrode material in batteries, as a conductor in electrical circuits, and as an additive for metals and alloys. "What we are seeing now is that most papers on graphene are about potential applications, or some new architecture or assembly processes aimed at new applications," says Hurt.

As graphene shows, there is significant overlap between nanomaterials and energy materials, as scientists look to the large surface area of nanomaterials to improve the efficiency of battery materials. There is also a significant overlap between nanomaterials and drug-related materials, which experienced the third largest growth in scholarly output, at 52%. Nanomaterials have been responsible for much of this growth, as scientists explore using various nanomaterials, including polymer micelles and metal nanoparticles, to delivery drugs or treat diseases directly. Cancer is a major focus of these efforts, as demonstrated by the number of cancer-related keyphrases, such as cytology, oncology and chemotherapy, showing high rates of growth.

> "A lot of nanomedicines and nano-diagnostic tools are being developed based on material knowledge," says Lou. "This is a very, very active area."

EOM materials had the dubious honor of being the subject of by far the most scholarly outputs, at 448,312, while also experiencing the lowest rate of growth, at 9%. Second and third largest number of scholarly outputs were seen for metals and alloys and polymers and plastics, respectively, both of which had over 100,000 outputs.

Now these figures are obviously influenced by the fact that there is some overlap between the different material classes. EOM materials, especially, is a broader class than some of the others and so will likely contain scholarly outputs that also appear in classes such as nanomaterials, ceramics, and metals and alloys. But it does clearly show that there remains a great deal of research activity in EOM materials, as there is in the four other more 'mature' material classes, which all experienced growth between 2012 and 2016.

Moreover, in all five of these slower-growing classes, certain keyphrases showed high rates of growth, indicating active areas of research. In EOM materials, it was infrared devices, photonics and optical fibers; in ceramics, it was ceramic materials, piezoelectricity and ferroelectricity; in metals and alloys, it was graphene, nickel and slags; and in biomedical materials, it was cell engineering, cytology and graphene.

In polymers and plastics, chains, elastomers and reinforced plastics were keyphrases that all experienced high rates of growth. Meanwhile, Krysztof Matyjaszewski, professor of natural sciences at Carnegie Mellon University, US, and editor-in-chief of *Progress in Polymer Science*, highlights gaining precise control over the macromolecular structure of polymers and developing new materials such as polymeric brushes and bioconjugates as particularly hot topics.

Over the past few years, China has overtaken the US to become the most prolific country in materials research, producing the greatest number of scholarly outputs between 2012 and 2016 for every material class apart from biomedical materials, where it was second behind the US (see Table 10).

The growth in China's research output has been substantial for most material classes over this period, including 130% for energy materials, 88% for nanomaterials and 74% in drug-related materials, driven by large increases in government funding for materials research. India is also investing heavily in materials research and its scholarly outputs have grown rapidly in response. Other major producers of scholarly output across all the material classes include Germany, Japan, and South Korea.

China may produce lots of scholarly output, but this output does not always have a particularly high impact, as measured by the FWCI and percentage published in the top 5% of journals. Scholarly output from the US had a higher FWCI and percentage published in the top 5% of journals than China for every material class apart from biomedical materials (see Table 11).

Singapore consistently produces high-impact research; the only area where it doesn't do as well under these metrics is polymers. Other countries producing high-impact work include Australia (polymers and plastics, nanomaterials, EOM materials and energy materials), the Netherlands (nanomaterials, energy materials, EOM materials and drug-related materials), Switzerland (metals and alloys, energy materials, drug-related materials, EOM materials and ceramics) and the UK (drug-related materials, metals and alloys, EOM, ceramics, and polymers and plastics).

> "Traditionally, the important players have been Europe (Germany, the UK), the US and Asia," says Lou. "But countries such as China, South Korea and Singapore are coming up the ranks very strongly recently, investing heavily and catching up quickly. They may be leaders in the next decade if this trend continues."

Perhaps due to the heavy investment in materials research from the Chinese government, Chinese researchers did not collaborate very much with industry between 2012 and 2016. For all material classes, the US had a greater percentage of industrial collaborations, although they were behind many other countries, especially in Europe. Researchers in the Netherlands collaborated extensively with industry in most material classes apart from metals and alloys, and ceramics. Other countries that are actively partnering with industry include Switzerland (polymers and plastics, nanomaterials, EOM materials, energy materials,

TABLE 10

Scholarly output 2012–2016 by China and US for each material class.

	Biomedical materials	Ceramics	Drug materials	EOM materials	Energy materials	Metals	Nanomaterials	Polymers
China	16,052	21,818	7,597	116,104	14,589	56,67	7,841	31,280
% increase	49%	18%	74%	32%	130%	30%	88%	14%
US	19,956	8,383	5,197	89,696	11,630	14,195	6,312	16,983
% increase	6%	−2%	47%	−11%	30%	2%	33%	44%

TABLE 11

Impact of scholarly output 2012–2016 for China and US.

Material class	China		US	
	FWCI	% in top 5% of journals	FWCI	% in top 5% of journals
Biomedical materials	1.79	26%	1.56	23%
Ceramics	0.75	7%	1.29	17%
Drug materials	2.05	44%	2.13	53%
EOM materials	0.89	8%	1.39	8%
Energy materials	1.8	26%	2.2	33%
Metals and alloys	1.02	18%	1.51	40%
Nanomaterials	1.93	34%	2.2	43%
Polymers and plastics	0.91	9%	1.35	28%

TABLE 12

Table 4: Patents relating to scholarly outputs for material classes 2012–2016.

Material class	Patent-citation count	Patent-citations per scholarly output
Drug materials	1,462	56.3
Biomedical materials	3,363	45.9
Nanomaterials	711	25.8
Polymers and plastics	2,893	25.3
Energy materials	1,302	23.5
EOM materials	7,724	17.2
Metals and alloys	2,109	13.9
Ceramics	801	11.4

drug-related materials and biomedical materials), Germany (polymers and plastics, nanomaterials, drug-related materials and biomedical materials), Sweden (nanomaterials, metals and alloys, EOM materials and biomedical materials), the UK (biomedical materials, drug-related materials, nanomaterials, ceramics, polymers and plastics, and metals and alloys), and Japan (ceramics, metals and alloys, EOM materials and energy materials).

In terms of patents, drug-related materials and biomedical materials appear to be particularly active, with the highest number of patent citations per 1000 scholarly articles (see Table 12).

EOM materials had by far the largest number of patents citing scholarly outputs, although that may just be because it also had by far the largest number of scholarly outputs. Interestingly, despite being a very active research area, nanomaterials generated the lowest number of patent citations, which may simply reflect the fact that many nanomaterials are at an early stage of development.

Nevertheless, according to Hurt, many nanomaterials have superb commercial prospects, especially graphene. "There have been some challenges around the commercialization of carbon nanotubes such as cost and safety, but graphene-based materials are doing better."

Materials classes such as metals and alloys and polymers and plastics are already huge commercial sectors, but this is mainly due to established materials such as aluminum alloys and polyethylene rather than new materials. In contrast, energy materials are experiencing rapid growth through the development of novel materials, especially energy storage materials, driven by the increasing need for more efficient, longer lasting batteries in electric devices and vehicles, as well as for storing renewable energy.

> "Energy storage is expected to grow so rapidly," says Yushin. "The market is already well over $50 billion but is going to become a multi-trillion-dollar market. In my opinion, energy material science will probably receive the largest commercial interest."

This also demonstrates how applications are driving the development of new materials, rather than the other way around. "It's mostly governed by applications; what people think would be important or should be important for the future," says Yushin. Because reaching that future will require a whole host of novel materials.

About the authors

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