A Landscape of Nanoscience and Technology Development

SCALING DOWN FOR A BRIGHT FUTURE

Produced by Springer Nature and supported by National Center for Nanoscience and Technology

SPRINGER NATURE

[Foreword]

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SMALL STEPS TO MAJOR CHANGE

Nanoscience is a cutting-edge research field at the core of chemistry, physics, biology and materials. It has had a profound impact on modern science as a key to the development of multiple disciplines. It's also pivotal to transformative manufacturing technologies with growing applications found in energy & environment, biomedicine, information devices and green manufacturing. Over the past two decades, countries and scientific institutions across the world have implemented nanoscience research and development plans, making way for the field's comprehensive and rapid growth. Due to China's early and continuous emphasis on nanoscience, the country is becoming one of the powerhouses leading nanoscience development.

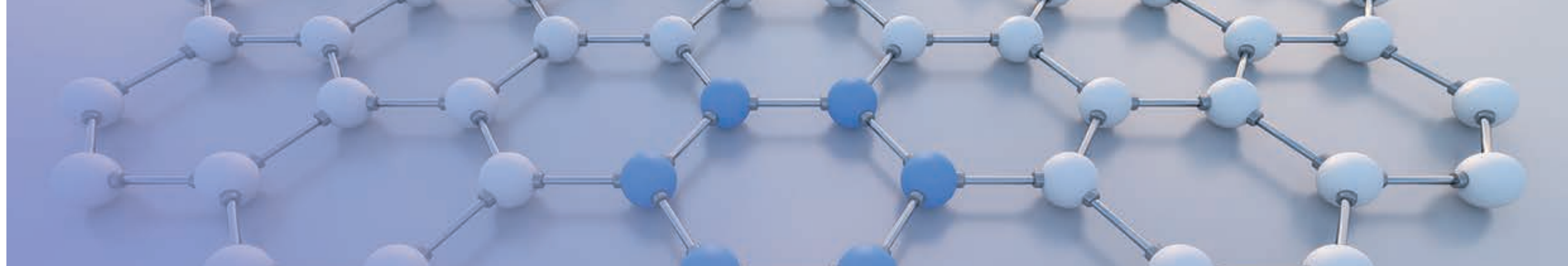
Scaling down for a bright future: A landscape of nanoscience and technology development, a report produced by Springer Nature, and supported by National Center for Nanoscience and Technology, provides a comprehensive picture of global nanoscience development in recent years. It combines big data analysis and infographics with expert opinions and interpretations from the perspectives of high-quality research papers, patents, key disciplines, technologies and sustainable development.

Based on bibliometric and citation analysis, this report incorporates the insights of global peers at the forefront of nanoscience research. As the report reveals, nanoscience and technology is developing rapidly around the world, making a huge difference. It is leading the way for physics, chemistry, materials and life sciences among other basic research fields. With ever-expanding applications, nanoscience is becoming an increasingly stronger pillar of industrial technologies.

Just like other endeavors, nanotechnology, in bringing rapid development, is also likely to raise new problems of environment, health and safety. These uncertainties and potential risks must be observed and investigated. However, nanotechnology development differs in that it pays close attention to potentially negative consequences from the very beginning rather than rely on 'develop first, clean up later' approaches. This means nanoscience is likely to become the first field that carries out systematic research on its possible adverse effects before large-scale application takes place.

The future of nanoscience and technology hinges on its contributions to global sustainable development. There is a need to strengthen basic research to lay a solid foundation for further growth of the field; to boost its catalytic effects on industrial technologies to more adequately meet the pressing requirements of energy and environment, healthcare, advanced manufacturing and artificial intelligence.

More extensive and effective cooperation at the global level is needed to build and improve the innovation chains and value chains in nanotechnology. We hope that through concerted efforts of global nanoscience researchers, more breakthroughs will come, with a broad effect on industrial technology innovation to ultimately benefit society. ■



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THE HUGE REALM OF THE NANOSCOPIC

Good things come in small packages. Nowhere is this adage more true than in the fields of nanoscience and nanotechnology. With features a billionth of a metre, smaller than the width of a human hair, the science and technology of the small has had a big impact on fields as diverse as medicine and quantum computing.

The word 'nanotechnology' was first used by Norio Taniguchi in 1974. The concepts behind it, however, can be traced back even further. Richard Feynman described a field that focuses on manipulating and controlling things on a small scale in his often cited 1959 lecture, 'There's plenty of room at the bottom.' Farther back, medieval artisans relied on nanoscale materials to decorate stained glassed windows, as did the Roman craftsmen that made the Lycurgus Cup in the 4th century AD. Yet for its history, the breakout moment for the field arguably came in 1981 with the development of the Scanning Tunnelling Microscope (STM), which allowed scientists to visualize individual atoms.

Since then, scientists have made nanoparticles, nanowires, nanotubes, nanosheets, nanostructured materials, and complex topological nanostructures—even nano sea-urchins. They have used these structures to make field-effect transmitters, biosensors and solar cells. They have developed nanoparticle-based cancer treatments, and nanostructured membranes for water purification. Nanotechnology has quietly become part of our daily lives, in ways few ever consider – as components in sunscreens, wrinkle-resistant clothes, and even golf clubs. Indeed, the global nanotechnology market is predicted to exceed USD 125 billion by 2024[1].

Meanwhile, nanoscience is rapidly developing as an interdisciplinary field, with growing research output, encouraged by strong governmental support. For instance, the United States launched its National Nanotechnology Initiative as early as 2001, which has received continued investment totalling almost USD 27 billion since its inception[2]. Similarly, China also recognized the importance of developing nanoscience and technology early on and funded several major research projects in the field.

This report will present a snapshot of the current state of nanoscience and technology research, supported by bibliographic data and expert interviews, with a particular focus on China's performance.

In Section 2, we will present a bibliometric analysis of nanoscience and technology's contribution to the basic sciences, using data from Dimensions, Digital Science's database of publications, grants and clinical trials, and Springer Nature's Nature Index, a database that tracks primary research articles published in high-quality science journals.

We will continue along those lines in Section 3, where we will conduct a cross-country comparison of nanotechnology research competitiveness including China, the United States, the United Kingdom, Japan, South Korea, Germany, France and Australia.

In Section 4, we use Springer Nature's Nano database, a comprehensive collection of nanomaterial data, patents, and literature references, to probe popular nanostructures and emerging applications.

We will supplement the analysis with interviews from Chinese and international experts in nanosynthesis, nanocharacterization, nanomedicine and nanodiagnostics, energy applications of nanomaterials, nanotechnology and the environment, and nanodevices. The experts will help to identify recent developments in these specific research fields, the challenges that must be overcome, and how they hope the fields will evolve in the future.

We conclude with a summation of our findings, along with a discussion of the role nanoscience and technology play in the global sustainable development goals, economic development, and environmental protection. ■

1. See https://www.researchandmarkets.com/reports/4520812/global-nanotechnology-market-by-component-and
2. See https://www.nano.gov/about-nni/what/funding

IMPORTANCE OF NANOTECHNOLOGY TO BASIC SCIENCE

As a study of matter at the nanometre scale, nanoscience is an interdisciplinary subject that cuts across a range of fields, from chemistry and physics to biology and life sciences, and it is playing an increasing role in advancing basic science.

To understand its contribution, we analysed high-quality papers tracked by Nature Index to examine the output and growth of nanoscience research within four broad fields of natural sciences—chemical, material, physical and life sciences. Publication data tracked in Digital Science's Dimensions database were also analysed for a longer-term overview of the growth of the field.

Growth of high quality publications in nanoscience

The Nature Index tracks primary research articles published in a selected group of 82 high-quality science journals. Using a keyword search of abstracts, titles and full text, nano-related articles published from 2012 to 2018 were identified in the Nature Index database.

The total number of nano-related articles in Nature Index grew by 52%, from around 6,900 in 2012 to slightly over 10,500 in 2018, with a compound annual growth rate (CAGR) of 7.3% **(Figure 1)**. This rate is significantly higher than that of all primary research articles tracked by Nature Index, which grew from less than 57,500 in 2012 to around 59,600 in 2018, an increase of only 3.7%. The disparity indicates that the observed growth of nanoscience research is not just a result of the expansion of high-quality papers tracked by Nature Index.

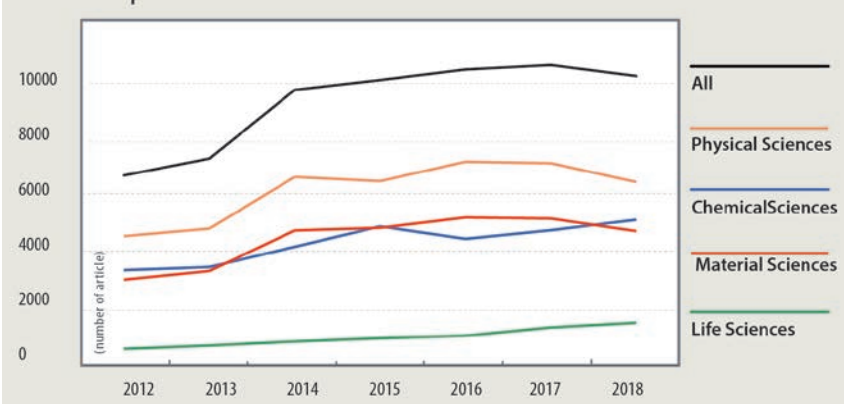
In the years between 2012 and 2018, the greatest increase in nano-related publications occurred in 2014, which saw a 33% increase from the previous year. Since then, the increase rate levelled off, with a slight drop of nano-related publications in 2018. The observed surge in 2014 coincides with upsurges in graphene- and nanotube-related articles in Nature Index journals. The number of graphene-related articles in Nature Index journals soared from around 1,900 in 2012 to more than 3,500 in 2018, with the fastest growth of 25% in 2014**(Figure 2)**. Articles on nanotubes saw a steady growth from 2012 to 2018, making the 22% uptick in 2014 very prominent.

Also, in early 2014, a paper reporting the fabrication of transistors using black phosphorous thin crystals was published, gaining a large number of citations and generating further investigations of two-dimensional materials, including two-dimensional phosphorene[1].

Correspondingly, articles discussing energy storage saw a 40% increase in 2014 from the previous year, based on analysis of the Nano database, as shown in Section 4. More specifically, in the Nano database, articles discussing solar cells increased by more than 2,000 from 2013 to 2014, the highest increase in article volume in the last 10 years. Several highly cited papers on perovskite solar cells were published around 2013 and 2014, reporting high power conversion efficiencies. These articles have attracted further attention to perovskite materials, leading to a booming of studies on solar cell technologies.

Based on the existing journal groups of Nature Index, nano-related primary research articles can be categorized into three broad fields—chemistry, physical sciences and life sciences[2]. In addition, primary research articles in a selected group of material science journals, along with selected research articles in Nature Index, identified using field of research (FoR) codes, are categorized as material science papers (refer to Appendix for more detailed description of the method).

FIGURE 1 | **NUMBER OF ARTICLES IN NANOSCIENCE 2012-2018, BY RESEARCH FIELD**



The field of physical sciences has the largest number of nano-related articles among the four broad fields **(Figure 1)**, mostly because nearly all of the material science articles and many chemistry articles can be categorized into physical sciences. Note that the number of nano-related articles in life sciences, while the lowest among the four research fields, more than doubled from around 610 in 2012 to nearly 1,560 in 2018. Life science has the fastest growth among the four research fields, with a CAGR of 17%, and is the only field that shows a continued increase in nano-related papers. Much of the booming was fuelled by research in nano-diagnostics and nanomedicine, such as the use of nanomaterials for drug delivery.

Material science has the second largest growth rate in nano papers, with a 57% increase from 2012 to 2018 and a CAGR of 7.8%. It overtook chemical sciences in 2014, 2016 and 2017. The growth curve of material science papers in nanoscience echoes that of nano-related physical science papers, which indicates a connection between the two fields. The growth of nano-related physical science papers is largely shaped by that of material science papers, which are a subset of the physical sciences. As outlined before, research on two-dimensional materials, such as graphene and phosphorene, solar cells (particularly, perovskite solar cells), and quantum effects might help explain the sharp increase in nano-related physical science and material science papers in 2014. As the publication data from Nano database show, studies on the quantum effect with graphene also grew rapidly around 2014.

In terms of quantity, nanoscience papers in chemistry track closely to those in material sciences. Again, this implies the interdisciplinary nature of nanoscience and nanotechnology. For instance, materials chemistry, which focuses on using chemistry

FIGURE 2 | NUMBER OF GRAPHENE AND NANOTUBE ARTICLES IN NATURE INDEX JOURNALS, 2012-2018

Obtained by tracking Nature Index journal articles in Dimensions

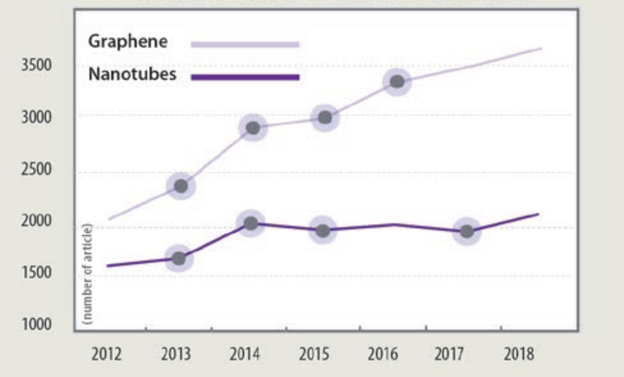
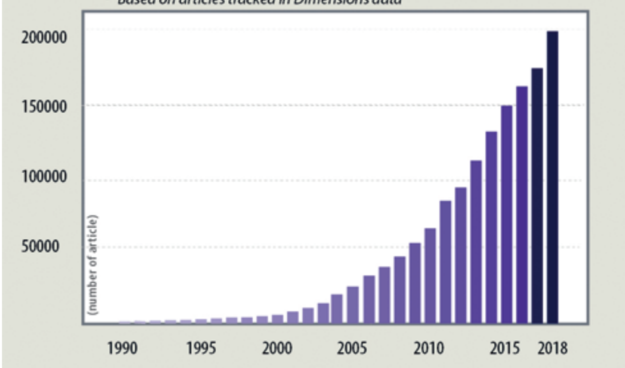


FIGURE 3 | GLOBAL RESEARCH OUTPUT IN NANOSCIENCE AND TECHNOLOGY, 1990-2018 (BASED ON ARTICLES TRACKED IN DIMENSIONS DATA)

Based on articles tracked in Dimensions data



methods to design and synthesize materials, is a key subdomain of materials sciences, suggesting that there is a significant overlap between the two fields. The number of nano-related chemical science papers grew steadily from 2012 to 2015, and after a drop in 2016, rose to its peak in 2018, with nearly 5,300 articles, surpassing material science papers.

Digital Science's Dimensions database, a research data platform linking publication, grants, patents and other relevant information, provides a longer-term overview of the growth of nanoscience research. Nanoscience research output[3] grew from less than 1,500 papers in 1990 to more than 205,000 in 2018, an increase of more than 130 times **(Figure 3)**. The steady growth in the 1990s could largely be attributed to the developments foundational to nanoscience. Carbon nanotubes and crystalline semiconductor nanowires were first grown in the 1990s, while an important STM technique that enabled atom-by-atom manipulation and the stimulated-emission-depletion microscopy technology were first reported.

On the foundation, the publication of nanoscience articles accelerated in the first decade of the 21st Century, largely powered by the development of two-dimensional materials and DNA nanotechnology, such as the isolation of graphene in 2004 and the invention of DNA origami in 2006. Publications grew from just over 6,000 articles in 2000 to nearly 67,000 in 2010, with a CAGR of 27%, marking the decade of the fastest growth in nanoscience research.

Since those heady days, growth has moderated but is still very much on the rise. Between 2010 and 2018, nanoscience research output increased at a CAGR of 15%. A portion of that growth can be attributed to the expansion of nanoscience into fields beyond material sciences and chemistry, particularly life sciences.

Growing role played by nanoscience and technology in basic research

For a closer look at the role played by nanoscience and technology in output of different research fields, we also used the Nature Index data to calculate the percentage of nano-related papers out of all high-quality research papers in a broad field.

A total of nearly 67,000 primary research articles published from 2012 to 2018 are nanoscience-related, accounting for 16% of the total number of Nature Index articles published in this period. The percentage increased from 12% in 2012 to 19% in 2017, but slightly dropped in 2018 **(Figure 4)**, possibly due to the decrease in nano-related physical science or more specifically, material science papers published in 2018, as shown in **Figure 1** above.

Unsurprisingly, materials science contains the largest percentage of nano-related articles, followed by physical sciences, chemistry, and then life sciences **(Figure 4)**. In general, more than half (51%) of all the quality material science papers published from 2012 to 2018 are nanoscience-related. In a yearly comparison, the percentage steadily increased, from 43% in 2012 to 54% in 2018, demonstrating an increasingly important role played by nanoscience and technology in shaping the development of this field.

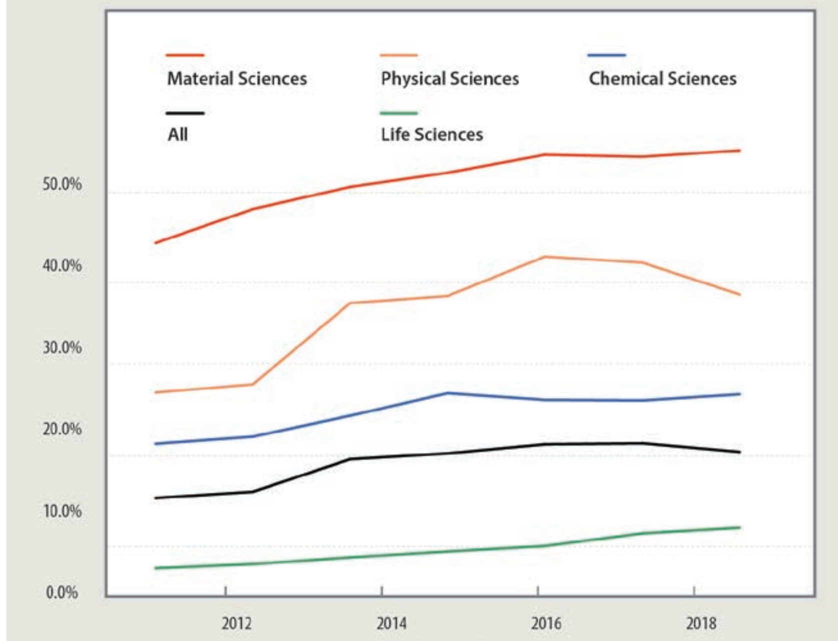
More than one third of all quality physical science papers published from 2012 to 2018 are nanoscience-related, the second highest among the four broad research fields. The percentage of physical science papers using nanoscience and technology grew from 25% in 2012 to 42% in 2016, but since then slightly declined **(Figure 4)**. Similar to the number of nano-related physical science papers, the biggest increase in the percentage was in 2014, which can possibly be explained by the growing research on two-dimensional materials and related applications in nanoelectronics as mentioned earlier.

Note that the percentages of nano articles in physical sciences are lower than those of material sciences, while in terms of the number of nanoscience-related papers, physical sciences makes a larger absolute contribution. This is simply because materials science is a smaller field in Nature Index than physical science, which, ranging from high energy physics to geology, includes a larger number of articles, and thus, inflating the number of nano-related physical science papers.

The percent of chemical science papers related to nanoscience and technology grew from 19% in 2012 to 25% in 2015, and since then, the growth levelled off. The percentages are much lower than those observed for material sciences, even though the number of nano papers in chemistry is not much different from that in material sciences. This is because in our classification of Nature Index journals, chemistry is a larger field including more journals than material sciences, thus, with more papers published between 2012 and 2018. Making up more than one fifth of chemical science research output, publications in nanoscience and technology still contribute considerably to the field of chemistry.

FIGURE 4 | PERCENTAGE OF ARTICLES IN NANOSCIENCE 2012-2018, BY RESEARCH FIELD

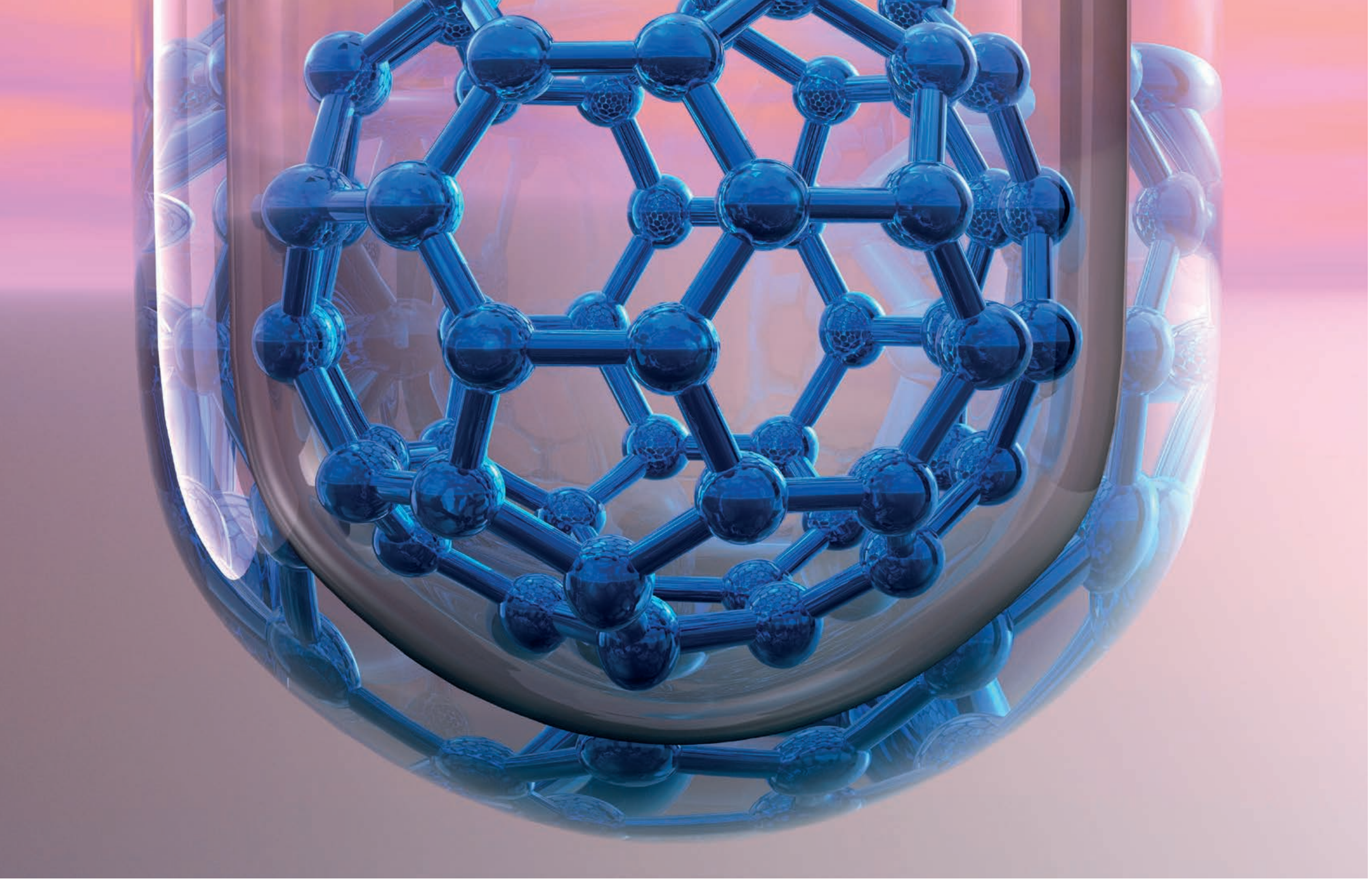
Note: The percentages are calculated as follows: number of nano articles in each broad field (All, chemical science, material science, physical science and life science) divided by the number of Nature Index articles in that field, so the denominators are different for different research fields.



The story in life sciences is slightly different. The percentage of nano-related papers is still quite low but climbing steadily. It grew from 3.5% in 2012 to 8.4% in 2018, suggesting that nanoscience and technology are playing an ever-larger role in the development of life sciences, including biomedicine.

In general, being a broad research field, physical sciences have the largest number and share of nanoscience research output. But when controlling for the size of the field, we see that it is in material sciences that nanoscience and technology play a most dominant role, represented by an increasingly larger percentage of material science papers using nanoscience and technology. While the role played by nanoscience and technology seems to be minor for life science research output, it is steadily growing. This trend suggests that nanoscience is becoming increasingly interdisciplinary, contributing to the growth of multiple basic science fields. ■

1. See Li, Likai; Yu, Yijun; Jun Ye, Guo; Ge, Qingqin; Ou, Xuedong; Wu, Hua; Zhang, Yuanbo (2014). "Black Phosphorus Field Effect Transistors". *Nature Nanotechnology*. 9 (5): 372–377.
2. For the list of journals in each broad field, please see https://www.natureindex.com/faq#subjects. Or refer to the Appendix for Nature Index journal grouping.
3. Note that journal publications in Dimensions database include not just primary research articles, but also perspectives, reviews, and for a small selected number of journals, news and comments. Although a small number of nano-related articles in Dimensions are not primary research output in a strict sense, all these publications reflect the growth of this field.



CROSS-COUNTRY COMPARISON OF RESEARCH OUTPUT IN NANOSCIENCE AND TECHNOLOGY

From thousands of papers published globally each year in the 1990s, to hundreds of thousands of publications annually now, the field of nanoscience and technology has emerged as a research priority in many countries, as demonstrated in the growing amount of primary nanoscience research published in major research powerhouses.

To understand the growth patterns in nanoscience research at a national level, and to understand the competitive strengths among large national contributors to research output, we used Dimensions and Nature Index data for cross-country comparisons. We also identified key institutions that contribute to the growth of nanoscience research.

A longitudinal view of cross-country comparison in nanoscience research

Using the Digital Science Dimensions database, we compared the growth of nanoscience publications from 1990 to 2018 among the eight top nations driving the field: China, the United States, Japan, Germany, South Korea, the United Kingdom (UK), France, and Australia.

Based on publication data tracked in Dimensions, all eight countries have seen increases in nanoscience publications from 1990 to 2018, a result of the booming of the field. But nowhere is that growth more pronounced than in China, where the number of journal articles in nanoscience grew from just 14 in 1990 to nearly 70,600 in 2018, at a CAGR of 36% **(Figure 5)**. The real takeoff was in the 2010s, when the increase from 2010 to 2018 in the number of nano papers amounted to more than 58,000. China's research output in nanoscience rose to be the highest of the world in 2011, far outpacing the other countries since 2012.

The rapid growth in China can be attributable to the strong governmental support, with ever-growing research funding. As early as the 1990s, the National Natural Science Foundation of China (NSFC) funded nearly 1,000 small-scale projects in nanoscience[1] . Around 2000, China's Ministry of Science and Technology (MOST) funded a national nanomaterial and nanostructure basic research project, providing sustained funding to fuel research in this area. With continued research funding support, China is positioned to extend its lead in nanoscience research in the coming decade.

Another rising star in nanoscience research output is South Korea. The number of articles it published in nanoscience grew from only 8 in 1990 to nearly 10,600 in 2018, at a CAGR of 29%. It is ranked last among the eight countries throughout most of the 1990s, but surpassed Japan to become the fourth largest contributor to nanoscience research in 2012, only slightly behind Germany.

Among the other countries in our analysis, Australia has the third highest CAGR at almost 22%, though due in large part to its smaller size it is consistently ranked seventh or eighth in number of nanoscience publications for most of the years in the period from 1990 to 2018. Likewise, the United States nanoscience research output grew at a CAGR of 18%, giving it the fourth highest growth rate among the eight countries we evaluated. That rate is not enough to prevent the United States from slipping behind China in 2011 to become the second largest contributor to nanoscience research output, a position it still occupies today.

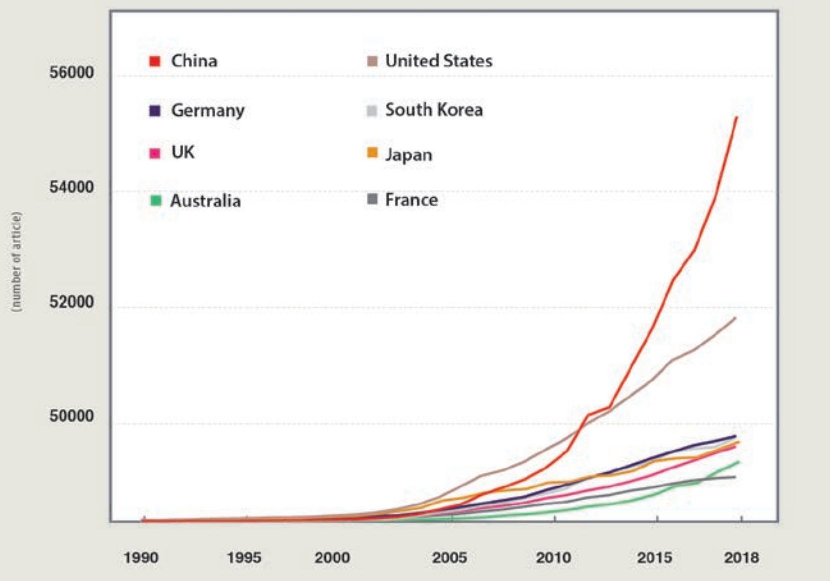
A cross-country comparison in high-quality nanoscience papers

For a closer look at the recent growth trends of quality research output in nanoscience and technology for the main research powerhouses, we used Nature Index data to compare the numbers of nano-related papers published from 2012 to 2018 by these eight countries.

When looking at nanoscience papers in Nature Index journals, the United States led the world throughout the period from 2012 to 2017 **(Figure 6)**. Its high-quality research output in nanoscience and technology grew by 43%, from 3,070 papers in 2012 to almost 4,400 in 2017. But in 2018, it dropped to slightly over 4,000 and was, for the first time, surpassed by China.

Though China surpassed the United States in the number of nanoscience publications in 2011, it still had a gap to close with the United States in high-quality nanoscience research for the years from 2012 to 2017. With the highest growth rate among the eight countries, China's high-quality nanoscience publications more than trippled from nearly 1,300 in 2012 to slightly over 4,100 in 2018,

FIGURE 5 | RESEARCH OUTPUT IN NANOSCIENCE 1990-2018, BY COUNTRY



a CAGR of 21%. In 2018, China overtook the United States as the global leader in high-quality nanoscience research output, a lead it is positioned to extend in the future.

Both China and the United States lead the rest of the pack by a wide margin. Germany, ranked third throughout 2012–2018, saw its high-quality journal publications in nanoscience growing from 885 in 2012 to only around 1,350 in 2018, a CAGR of 7%. The UK follows in the fourth position and has a growth pattern (a CAGR of 10%) very similar to that of Germany. Their growth rates (calculated in CAGR), though higher than that of the United States, are flat compared with China's.

For South Korea, its rapid growth in nanoscience research output is not replicated in high-quality nanoscience publications, suggesting that it could still improve the quality of its research in this field. France and Australia remained at the seventh and eighth in quality research output in nanoscience throughout 2012–2018.

As articles produced in international collaboration can be counted as research output in more than one country, we also compared quality research output in nanoscience and technology (as tracked by Nature Index) using the fractional count (FC). This measure takes into account the percentage of authors from an institution (or a country) and the number of affiliated institutions (or countries) per article, and all authors are considered to have contributed equally to the article.

Seen through the lens of FC, the growth patterns in quality nanoscience research for the eight studied countries are generally similar to those observed when using article counts. But some distinctions are worth noting. Taking FC into consideration, the United States appears to have peaked in 2014 rather than 2017, with a slight decline in FC of nano-related research output from 2014 to 2016 **(Figure 7)**. This suggests a higher degree of international collaboration in the nanoscience research output of the United States in this period.

In addition, China appears to have led the United States by a larger margin in 2018 when using FC, which might also be a result of the greater international collaboration in that year for the United States. It might also be interpreted as a stronger dependence on internal resources for China's nano research output, compared with that of the United States.

Germany remains third in terms of its contribution to nanoscience research output when using FC. South Korea is consistently ranked the fourth in FC between 2012 and 2017, only surpassed by the UK in 2018. When using FC, nano research output of the UK is also lower than that of Japan in the three years from 2014 to 2016. This suggests a greater amount of international collaboration in nano-related research by UK, compared with the two Asian countries.

France and Australia remain ranked at seventh and eighth, respectively, in nanoscience research output when using FC. As countries with high level of international collaboration in their quality nanoscience research output, their gaps with the other countries have slightly widened.

Leading institutions in nanoscience research

The top 100 institutions producing quality nanoscience research in Nature Index were also identified. In line with the leading positions of the United States and China in nanoscience research, the majority of the leading institutions in nanoscience and technology-related research output are from these two countries. Among the top 100 institutions with the highest FC of nano-related research output in 2018, 33 are from China, and 30 are from the

FIGURE 6 | QUALITY RESEARCH OUTPUT IN NANOSCIENCE (IN ARTICLE COUNT) 2012-2018, BY COUNTRY

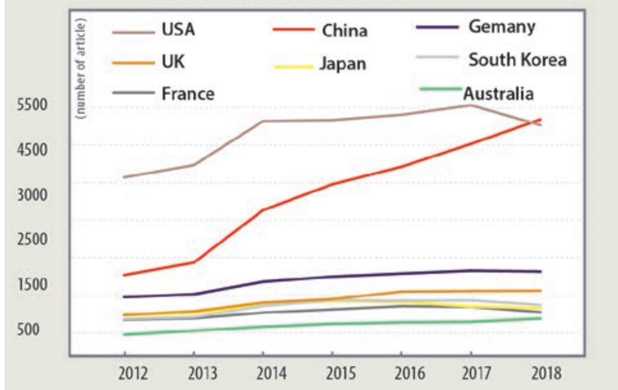


FIGURE 7 | QUALITY RESEARCH OUTPUT IN NANOSCIENCE (IN FRACTIONAL COUNT) 2012-2018, BY COUNTRY

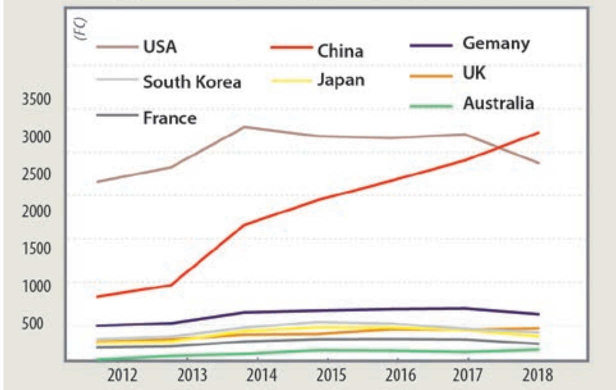
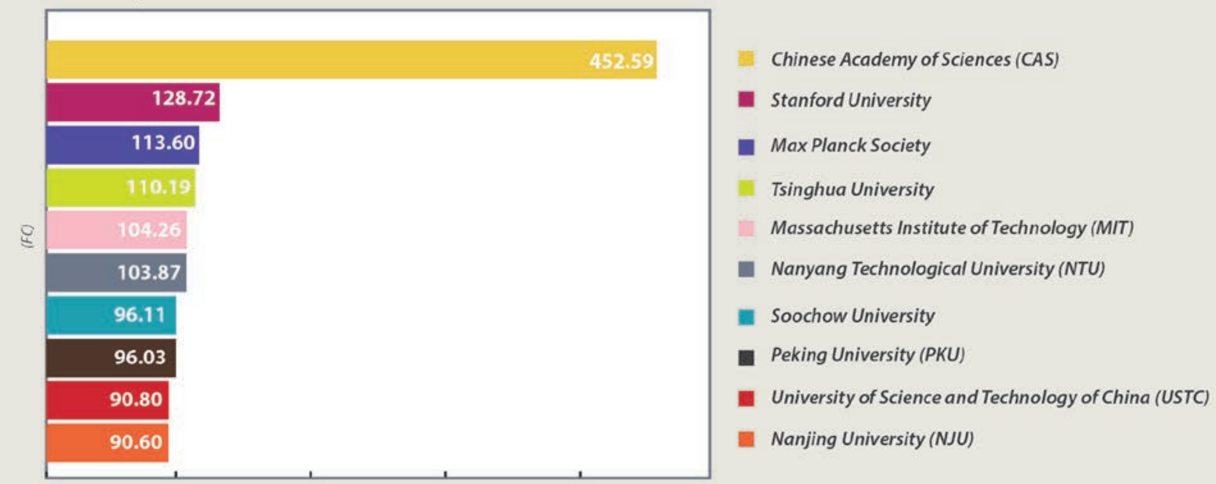


FIGURE 8 | LEADING INSTITUTIONS IN NANOSCIENCE-RELATED RESEARCH OUTPUT IN 2018



United States. Seven institutions are from South Korea, six from Germany, and five are from Japan. The eight countries under study account for 88% of the top 100 institutions.

Looking at the top 10 institutions, the dominance of Chinese institutions is clear, with six institutions on the list **(Figure 8)**. The Chinese Academy of Sciences (CAS), including its institutes and state key laboratories, has the highest FC of nano-related research, leading the other institutions on the top 10 list by a large margin. While the sheer size of CAS may help explain its contribution to nanoscience research, its top ranking in high-quality research output also signals its strength.

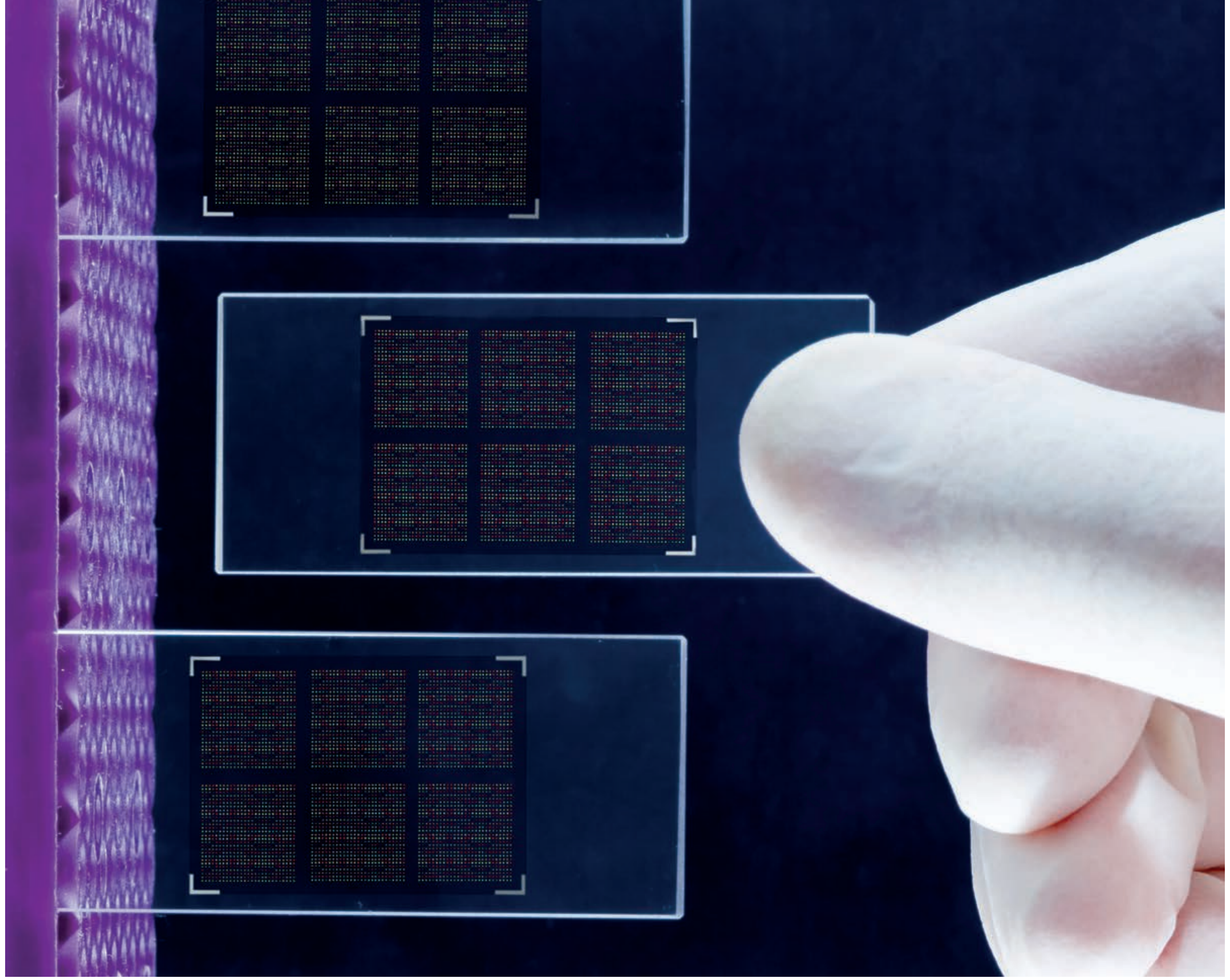
The second largest institution contributor to quality nanoscience research output in 2018 is Stanford University in the United States. Its FC is less than one third that of CAS, which is not surprising considering the size difference. Stanford University is followed by Max Planck Society in Germany, which, as with CAS, also includes all of its associated centres and institutes. It is the only European institution in the top 10 list.

Another American institution on the top 10 list is Massachusetts Institute of Technology (MIT), ranking the fifth in terms of the FC of nano-related research output. It is closely followed by Nanyang Technological University in Singapore.

In general, the global comparison shows the leading role played by the United States and China in the landscape of nanoscience and technology research, including quality research output, and particularly, a rapidly growing contribution by China.■

1. See Bai, Chunli. Ascent of Nanoscience in China. *Science* 2005, 309: 61-63.

A PROMISING FUTURE FOR INDUSTRIAL APPLICATIONS OF NANOSCIENCE AND TECHNOLOGY



From nanosheets to nanotubes, nanomaterials vary significantly in form and type. As such, they also have diverse applications, which range from catalysts for energy conversion to nano devices for electronic uses. They present great potential for uses in various industries, though for many promising nanotechnologies obstacles remain with commercialization and production at scale.

Using the Nano database, we investigated popular nanostructures and related applications to assess the state of development within specific areas of nanoscience and technology. We also conducted interviews with Chinese and international nanoscience experts to better understand the research and R&D trends in specific research spaces to identify promising opportunities, as well as persistent challenges.

Understandings from the Nano database

To identify popular and commonly studied nanostructures, as well as emerging applications, we used the Nano database, a platform developed by Springer Nature to help researchers keep track of the latest research in nanoscience and technology. The database includes detailed information on properties, applications and preparation methods of thousands of nanomaterials and devices gleaned from peer-reviewed journal articles on nanoscience. The Nano database also includes nano-related patent information, which helped to inform our analysis as well.

Popular nanostructures

Based on analysis of the Nano database from 2010 to 2018, nanoparticles stand out as the most frequently studied structure. More than 270,900 journal articles referenced them between 2010 and 2018. In this period, the annual number of articles concerning nanoparticles more than tripled from about 13,000 articles in 2010 to nearly 40,000 in 2018 **(Figure 9)**.

Graphene is another very popular nanomaterial. It did not gain much attention until after 2004 when it was first isolated from graphite, but interest in it has grown since. The Nano database tracked more than 2,100 graphene-related articles in 2010. That the number surged to more than 10,000 in 2014 and to more than 21,000 in 2018, approximately a 10-fold increase in less than a decade **(Figure 9)**.

Though farther down the development curve, other emerging nanomaterials are gaining in popularity, namely nanosheets, nanowires and nanocrystals. Studies on nanosheets in the Nano database were only slightly over 800 in 2010, but increased to more than 11,000 articles in 2018. Likewise, the numbers of articles that explored nanowires and nanocrystals saw significant growth. Both areas grew from around 3,800 articles in 2010 to slightly under 10,500 in 2018 **(Figure 9)**.

In the realm of patent applications, our analysis of the Nano database mostly echoed the trends in research output. Popular structures are nanoparticles, graphene, quantum dots, nanowires and nanocrystals.

As with research output, nanoparticles dominate nanoscience and technology patents in the Nano database. This is largely because the technology is more mature than other applications and the perceived opportunities are so great. Potential applications span drug delivery and medical imaging, consumer health and fitness applications and, even, environmental applications, such as in water treatment and air or soil pollutant remediation.

The number of patents on nanoparticles grew from above 30,000 in 2010 to more than 36,000 in 2014. Since then, the number has fallen slightly, dropping to just over 27,000 in 2017 and further down to just over 14,000 in 2018 **(Figure 10)**. The decline in 2017 and 2018 could be an artefact of incomplete patent data tracked in these two years due to the requirement for a confidential period associated with patents. Thus, we only focus on patent data from 2010 to 2016 for the analysis.

In that same period, graphene-related patents also saw consistent and rapid growth, increasing from more than 5,400 in 2010 to nearly 24,000 in 2016 **(Figure 10)**. Though the number dropped in 2017 and 2018, due to the incomplete data collection, it grew higher than the number of nanoparticle-related patents in 2018. That growth was supported by an increasing research output and an acknowledgement of graphene's potential in industrial use, whether in the energy industry, with improved lithium batteries, or in the electronics industry, with advances in super capacitors and computer chips.

The growth of graphene related patents also benefits from the growth in large-scale production capacity, particularly in China. According to the Global Graphene Industry Report 2017, released by the China Innovation Alliance of the Graphene Industry, China ranks first in patent applications for graphene technology, and also has the most graphene manufacturers[1].

The number of other promising technologies grew steadily between 2010 and 2016. Patents based on quantum dots and nanowires also grew rapidly, though not as dramatically as those on graphene. The former increased by 63% from 2010 to 2016, while the latter saw a 48% increase in the same period. The number of patents exploring nanosheets grew from fewer than 300 in 2010 to approximately 1,300 in 2016. This is generally consistent with the rapid increase observed for the number of articles studying nanosheets.

Popular applications of nanomaterials

The Nano database also tracks various applications of nanomaterials discussed in research articles. Based on articles published between 2010 and 2018, popular applications of nanomaterials are electronics, catalysis, drug delivery, optoelectronics, and energy storage. The number of articles that have explored applications in electronics far exceeds that of the other popular

FIGURE 9 | POPULAR NANOSTRUCTURES DISCUSSED IN JOURNAL ARTICLES, 2010-2018

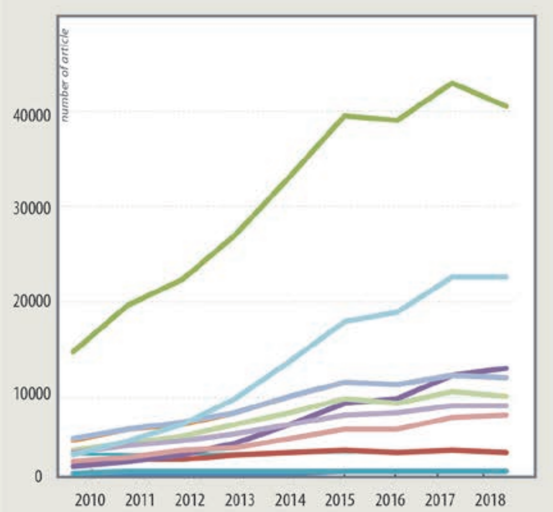
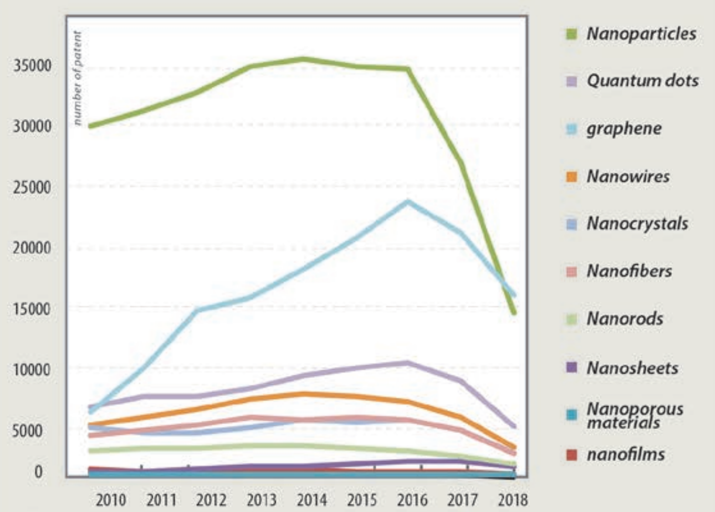


FIGURE 10 | POPULAR NANOSTRUCTURES IN FILED PATENTS,2010-2018



applications, rising from fewer than 31,700 in 2010 to more than 86,000 in 2017, an increase of more than 170% **(Figure 11)**. Though that number dropped to less than 82,000 in 2018, electronics remained the most popular nanotechnology application in terms of the amount of associated research output.

Catalysis is the second largest application area discussed in research articles published between 2010 and 2018. The related research output increased from about 5,000 articles in 2010 to more than 15,000 articles in 2017, though the number slightly dropped below 15,000 in 2018 **(Figure 11).**

Drug delivery is the third most popular application, as defined by the number of nanotechnology-related articles published between 2010 and 2018 that have discussed it. That number nearly tripled from more than 3,700 articles in 2010 to more than 11,000 in 2017, though it fell slightly below 11,000 in 2018. Optoelectronics closely follows as the fourth most popular application area based on the total number of articles published between 2010 and 2018 **(Figure 11)**.

In terms of growth areas, research output on energy-related applications increased the fastest, with the highest rate from 2010 to 2018 of all the popular applications. The number of nano-related articles that have discussed energy storage increased from around 1,200 in 2010 to slightly fewer than 12,000 in 2018 **(Figure 11)**. Similarly, the application areas of layered materials, medical devices and optoelectronics have all seen significant growth rates in terms of research output, though not as dramatic as the growth rate in energy storage.

Analysis on patent data shows that popular application areas of nanotechnology include electronics, drug delivery, paint, catalysis, and diagnostics **(Figure 12)**. While the number of patents on electronics remains the highest, as with its number of research articles, the popularity of biomedicine-related applications, like drug delivery and diagnostics, is significant. It shows focused attention on health applications and a high demand for technology innovation in the biomedicine industry.

The number of patents on catalysis is also high, but energy-related patent applications, like energy storage and power generation, are fewer than those on diagnostics and paint. It suggests that the use of nanotechnology in paint or biomedicine industry is more common than in the energy industry. But with the large number of articles discussing the use of nanotechnology for energy storage or generation, the application potential for nano energy is high.

Insights from insiders

Perspectives from experts in nanoscience and technology, obtained via interviews or literature review, inform our understanding of the prospects for nanotechnology application in different industries. Exciting recent developments in different areas of nanotechnology, from nano electronic devices and nano energy materials to nanomedicine and micro-nanoprocessing, are discussed, along with challenges and opportunities in these different research spaces.

Nanosynthesis

The global nanomaterials market is expected to reach USD 55 billion by 2022[2] . To realize the potential of nanotechnology-based devices, scientists and engineers must be able to grow nanomaterials to order with a high degree of precision and repeatability. Some of the major challenges in this field include: reproducibility, control of chemistry,

FIGURE11 | POPULAR APPLICATIONS OF NANOTECHNOLOGY DISCUSSED IN JOURNAL ARTICLES, 2010-2018

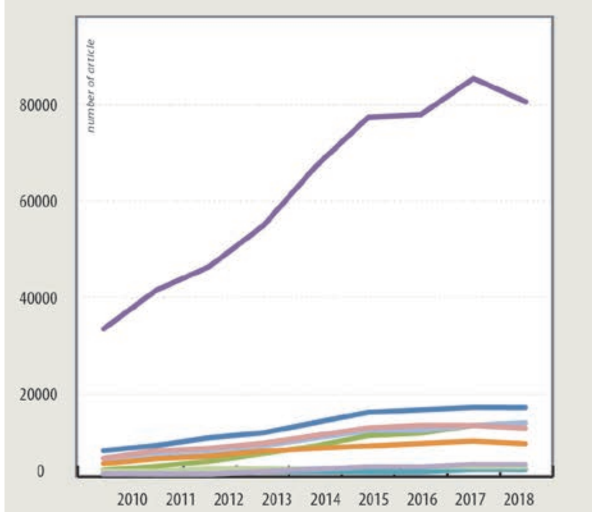
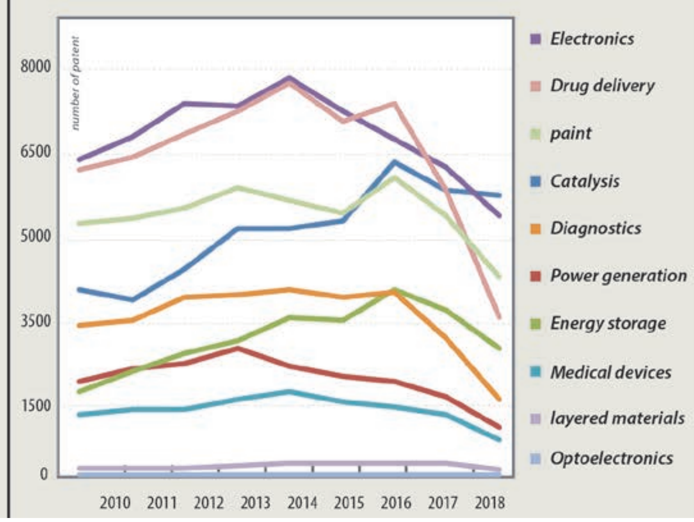


FIGURE 12 | POPULAR APPLICATIONS OF NANOTECHNOLOGY IN FILED PATENTS, 2010-2018



structure, and particle size.

Synthesis and/or fabrication must also be commercially scalable — "one needs nanomaterials that can be produced in macro quantities to make difference in the world," as a researcher explains.

"Methods of soft chemistry at room or slightly elevated temperature are the most promising for scale-up of nano-materials," an expert says. Other approaches gaining traction for the synthesis of two-dimensional (2D) materials are selective etching and topochemical synthesis.

As shown above in the bibliometric analysis, two-dimensional (2D) materials have garnered intense interest, particularly after the isolation of graphene in 2004, thanks to their intriguing physical, optical and electronic properties. Other examples of such materials include molybdenum disulphide (MoS_2) and other transition metal dichalgonides, silicene — a silicon analogue of graphene — hexagonal boron nitride, and MXenes.

"The synthesis of dozens of 2D carbides and nitrides (MXenes) is the most exciting development of the past decade," says one scientist. MXenes are two dimensional sheets of transition metal carbides or nitrides made from MAX phases — ceramics described by $M_{n+1}AX_n$, where M is a transition metal, A is aluminium or silicon and X is carbon or nitrogen, and n is 1 to 3. With high conductivity and flexibility, MXenes are of interest in a range of energy storage and water purification technologies.

China is leading the field in MXenes, both in terms of number of papers and patents. Stable phases of more than 200 MXenes have been theoretically predicted, in the coming years researchers hope to experimentally realise more than 100.

Scientists will still need to hone synthesis methods capable of making structures less costly and more efficiently to meet the industrial demand and realise wider application of nanomaterials and nanotechnology.

Nanocharacterization

Scientists and engineers need to be able to confirm that the nanomaterials they are making have the intended size, shape, crystal structure and elemental composition. Scanning and transmission electron microscopy (SEM & TEM) remain the most popular methods to characterize nanomaterials, but they come with limitations. Improved nanocharacterization approaches could move the field forward.

Of the emerging nanocharacterization methods, liquid cell TEM allows for measurements to be taken in liquid, for example, during the growth of nanoparticles in solution. High-resolution TEM can image the internal structure of the nanostructures, while electron tomography is able to capture 3D images of nanostructures. Cryo-electron microscopy (cryoEM), the subject of the 2017 Nobel Prize for Chemistry, is another method that can be used to visualize nanostructure growth.

In 2013, a cryoEM method called microcrystal electron diffraction (MicroED) was developed. It allows rapid, unambiguous determination of small organic molecules, and is already being used to study protein crystal structures, becoming another valuable tool in structural biology[3]. As electron diffraction is sensitive to charge and chemical bonding, it can potentially be used to directly visualize these key characteristics of protein structures. In 2018, the technique was used to obtain structural information from nanocrystals at resolutions of less than an angstrom. Further development of MicroED possibly requires improved specimen preparation that takes into account the biological feature of fragile protein crystals and preserves their structural details[4].

New developments in nanoscale characterization also lie in the in-situ and in-operando techniques. Usually used for studying catalytic materials and activities, the former allows high spatial-temporal resolution, while the latter couples characterization during the actual reaction condition (in-situ) with simultaneous measurement of catalytic activity and selectivity. They enable determining material structure and understanding its performance at the same time, helping to elucidate structure-function relationships of materials. Advances in these techniques, such as X-ray absorption spectroscopy and scanning tunnelling microscopy, will sharpen our understanding of catalytic reactions and enhance experimental design.

As the level of detail and control required in nanostructures for specific uses increases, so too must the level of information obtained from characterization techniques, to ensure that the materials produced — particularly for commercial applications — are uniform, reproducible and of acceptable quality. With reproducible and reliable characterization of nanomaterials, improved interpretation of characterization results and control of nanomaterial structure-function relationships, we are expected to transfer nanotechnology to more real-world applications.

Nano devices and information technology

Given their unique electrical, optical, magnetic and other properties, as well as their small size, nanomaterials are popular for uses in electronics, as our analysis suggests. From nano transistors to plasma displays and even quantum computers, nanomaterials allow, or could allow, enhanced computing capabilities with lower weight and power consumption.

A big challenge in the information industry is meeting the increasing demand for high-performance computing, according to an expert on nanoelectronics. As silicon-based chips are reaching their limit, carbon nanomaterials, such as graphene or carbon nanotubes, are giving Moore's law a new lease of life. They release less heat and consume less power, allowing a higher packing density than silicon materials. This means that more transistors can be crammed on a chip, leading to faster, and more energy-efficient integrated circuits, which are also less costly.

A recent exciting development is a three-dimensional chip based on carbon nanotubes, which combines data storage and processing, says the expert. "With a multi-layer structure, they have potential to improve the chip performance by hundreds or thousands of times, compared with current silicon-based ones."

Beyond chip design, carbon nanotubes, with their unique structure and high-sensitivity, could make ideal sensor materials, with promising application in the Internet of Things (IoT). New developments include combining carbon nanomaterials with machine learning technology to achieve high sensitivity and selectivity, as well as greater sensor accuracy. One exciting opportunity that is emerging lies in brain machine interfaces (BMI), where the confluence of artificial intelligence (AI) and nanotechnology are likely to enable BMI that can learn and adapt to changing demands[5].

Though heavy with promise, carbon nanomaterials are currently only used in a small number of electronic devices and sensors. As silicon-based devices will still meet most needs for the next couple of years, the calls to replace them are not too loud yet. In addition, many lab findings or patents are still a long way from commercialization. In order to drive commercialization forward, says one expert, "long-term commitment and more investment are needed to promote wider use of carbon nanomaterials."

In China, big investment into basic science research has led to growing research output in the area of carbon nanomaterials for electronic use. While China is already leading in nanoscience-related journal publications, it still has a gap to close in turning its research breakthroughs on carbon nanomaterials to disruptive technologies, according to an expert in the field. "Building an industry based on carbon nanomaterials still takes time and requires national government support," he said. And this is an issue not just for China, but also for the other big research powerhouses in nanoscience.

> "A big challenge in the information industry is meeting the increasing demand for high-performance computing."

While applied research may need some guidance and planning, this does not mean that careful government oversight is needed for developing research, the nano expert emphasized. "Basic research should be curiosity-driven, where researchers should be encouraged to explore freely, based on their interest," he said. "It has a different purpose from applied research, and the two should be evaluated separately."

Looking into the future of nanoelectronics, the use of nanomaterials will probably not be just confined to electronic devices, but extend to human-like systems or robots, according to one expert interviewed. The emerging nanomaterials-based smart skin technology that helps to sense the world and is self-powered is an example. With the marriage between nanotechnology and the AI technology, the future may see the development of a system that can also perceive the world, and make decisions.

Nanomedicine and nano-diagnostics

Results from the Nano database suggest that nanomedicine, either in published research articles or filed patents, is another popular nanotechnology application. As an emerging, interdisciplinary field, nanomedicine has grown in recent years. Driven by growth in areas such as drug discovery, regenerative medicine, diagnostics and medical imaging, nanomedicine already permeates the biomedicine industry, with widening application potentials. Common examples include nano drug delivery systems and nano-enabled sensors for disease diagnosis, as shown by Nano database results, along with some anti-tumour nanodrugs that are already in clinical use.

One exciting discovery, according to interviewed experts, is the recent development of nanorobots that can accurately deliver drugs and control their release. The new, intelligent drug delivery system uses programmed DNA, folded to encapsulate a drug payload, which travels the bloodstream. Once it locates the target tumour, the DNA would unfold and dispense a protein that causes blood clotting, leading to death of cancer cells[6].

"By integrating nanotechnology with molecular biology, this breakthrough will open a new field for nanomedicine," says the lead author of the study, an expert in nanomedicine. The programmed DNA technique was tested in mice with positive results in fighting breast cancer cells.

In nano diagnostics, recent advances include the use of flexible electronics as sensors to monitor neural activities[6]; high-speed nanopore DNA sequencing technology; liquid biopsies based on micro/nano sensors for early cancer detection; and nanoparticles that can be used as contrast agents for imaging, as well as for monitoring treatment effects of nanodrugs, combing diagnostic and therapeutic functions. Each one of these areas offers growth and opportunity.

One area that bears more investigation is the stability and safety of nanodrugs, say interviewed experts. Nanodrugs, usually based on self-assembled nanoparticles, can be highly active given their small size and complex structure. They could, one day, reduce the damage to human organs caused by traditional drugs, but much remains unknown, most particularly their potential toxicity and immunogenicity.

To facilitate the safe development of nanodrugs, says one expert, "we should also help improve public understanding of nanomedicine, highlighting that nanodrugs may not always be toxic, yet are not omnipotent either."

"Nanomedicine is not magic, and will not completely replace traditional medicine," says another. "They may complement each other, growing hand-in-hand."

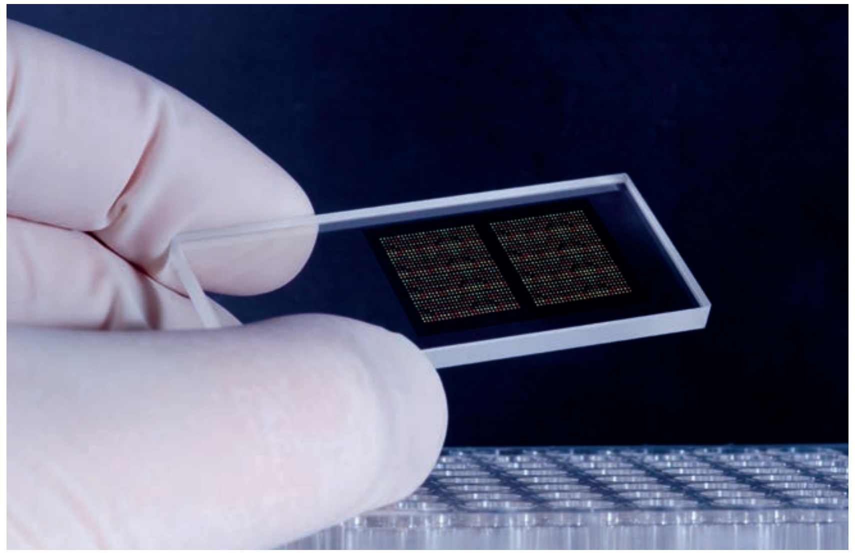
As with other areas of nanoscience, China is developing rapidly in nanomedicine. Particularly, it has produced many quality studies on nano toxicity and bio-safety, enzyme nanoparticles and smart nanorobots. However, there is still a lot of low-level repetitive work, and more systematic planning is needed to allocate research resources more efficiently. Also, China still has a gap to close in translating and applying its research results into clinical settings, says a nanomedicine expert.

Further development of nanomedicine requires a more established theoretical framework and closer integration between nanotechnology and biomedical research. "Our research should be guided by clinical needs," says an expert. "And we need more collaboration with biology and biomedical researchers, even clinicians."

> "Nanomedicine will become a core technology enabling smart healthcare."

In addition, efforts are needed to reduce the cost of nanomedicine, by setting up a system to advance the research and technological innovation, and by engineering technologies to fabricate nanodrugs at industrial scales.

"I hope nanomedicine will soon be applied in early diagnosis and treatment of major diseases," says one expert about the future of the field. "It may be able to turn cancer into a chronic disease, significantly improving patients' life quality," adds another. The integration with AI technologies is also promising. "Nanomedicine will become a core technology enabling smart healthcare."



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Nanotechnology and energy

Nanotechnology, according to one expert, is both disruptive and distributed and, in as much, could change the energy market as dramatically as smart phones changed telecommunications.

As mentioned earlier, results from the Nano database suggest that energy applications are, indeed, a hot topic for research articles on nanoscience and technology, and with good reason: Market research reports predict that the global market for nanotechnology in energy applications will grow from USD 5.7 billion in 2018 to USD 10 billion by 2023[8] .

Within energy, experts identified a number of broad challenges, including stability, cost, sustainability and scalability. Energy devices must be "cheap, durable, and life cycle sustainable," says one expert.

Nanotechnology could address each one of these broad challenges. For example, to make renewable energy more commercially viable, the efficiency of solar cells could be increased by incorporating nanostructured materials such as quantum dots and perovskite. Similarly, carbon nanotubes could be used as electrodes in thermocells to generate electricity from waste heat.

Nanomaterials could also be used to improve the performance and capacity of rechargeable batteries. They are particularly promising as components in the next generation of high-energy battery technology, according to one expert. Examples include nanostructured lithium metal and silicon anodes, as well as sulphur cathodes for next-generation, high-energy lithium batteries.

They also could have roles as catalysts, which are used to increase reaction rates. For the production of clean fuels, such as hydrogen, where current methods are energy-intensive, or reliant on expensive catalysts such as platinum, nanostructured catalysts are a must for commercial viability.

A major development in nanocatalysis is metal-free heterogeneous catalysis, including carbocatalysis, says one expert, where covalent carbon structures, such as graphene-based materials, can perform the same function as enzymes, but in all solvents and temperature ranges. These carbocatalysts may be used, not only in chemical catalysis, but also in photocatalysis and electrocatalysis.

Looking a bit further ahead, some of the major challenges in this field, experts predict, involve mobile safe energy storage for electric cars, with high energy density, long cycle life and capable of fast charging; storing energy for grid-scale use with seasonal variation; converting carbon dioxide into useful products; and efficiently harvesting and making use of waste heat. Nanotechnology could be harnessed to address these challenges, driving the new energy industry.

Thanks to considerable growth over the last two decades along with continued support and funding from the government and "the decline of the American funding culture," China has emerged as a leader in the junction of nanotechnology and energy, "Number 1, by volume and partly by quality," according to one expert. "There are many exciting research results from Chinese scientists spreading over all areas of energy technology," another adds.

Green nanotechnology

Nanotechnology can be harnessed to reduce potential health and environmental risks, addressing sustainable development challenges. Examples range from the use of nanopores for water treatment, to the development of solar cells that convert sunlight to electricity.

"Green nanotechnology also means synthesizing nanomaterials that are non-toxic and non-harmful, and minimizing the possible harm associated in the fabrication or manufacturing processes of nanomaterials," says an interviewed expert.

One example is the development of green catalysts, a pillar of green chemical engineering. Many conventional catalysts contain heavy metals, such as mercury, which can be a hazardous pollutant. The development of nitrogen-doped carbon nanotubes, which are found to be active in acetylene hydro-chlorination reaction, provides an effective and non-toxic alternative for producing polyvinyl chloride, a solid plastic widely used in construction, healthcare, electronics and more.

In the printing industry, nanomaterials are also used for coating to avoid chemical waste production, primarily caused by toxic photosensitive materials used for treating printing plates. Green printing technology can change the conventional printing processes and lead to high-resolution printing, achieved by polymer self-assembly processes. The technology is also applicable in printing electronic circuits, dyeing fabric, and 3D printing, providing an eco-friendly solution to a range of industries.

Concerns exist about the expanding use of nanotechnology and nanomaterials. One pressing issue is the perceived health threat of nanoparticles, which are already used in consumer products like sunscreens and paints, and can be inhaled or enter our bodies via skin. Contaminated metals in carbon nanotubes may also damage health.

"The long-term environmental impacts of large-scale use of nanomaterials and nanotechnology are still unclear and cause disputes," adds an interviewed expert. "More studies on these are needed if we want to have large-scale, wide applications of nanotechnology."

Particularly in China, where heavy investment has generated large output in nanoscience research, studies on the environmental impacts of nanotechnology are still lacking, compared to other major national contributors of nanoscience research, notes an expert. China is not short of studies on using nanotechnology to address environmental pollution problems or developing green nanomaterials. For instance, in water treatment nanotechnology, green catalysis, and green printing technologies, China is leading in the world. However, more safety studies, especially longitudinal studies are needed to evaluate the possible impacts of large-scale and long-term use of nanotechnology, urges one expert.

This kind of impact assessment is important for promoting industrial application, as well as public acceptance of nanotechnology. Further exploration at the nanoscale to reveal new mechanisms and basic research on the relationships between nanostructures and their properties may help improve our understanding of the environmental and health effects of nanomaterials. For promoting industrial use, "independent third-party agencies may be needed to evaluate potential side effects, and perform systematic studies on how to bring technology from lab to market, and how to safely apply it," says one expert. "We need a collaborative system that enables close interactions between academia, industry, market and the government." The true development and rollout of green nanotechnology require collaborative participation of all these players.

"Independent third-party agencies may be needed to evaluate potential side effects, and perform systematic studies on how to bring technology from lab to market, and how to safely apply it."

In summary, application of nanomaterials and nanotechnologies is growing. According to data from the United States Patents and Trademark Office (USPTO), the number of published nanotechnology patents grew to 20,187 in 2017, a 3.2% increase from 2016[9] . And among this, 9,145 were granted patents. Considering all the patents registered either in USPTO or European Patents Office (EPO), the share of nanotechnology patents to total patents was around 2.5% in 2017[10] . In China, nanotechnology patents accounted for 3.4% of all its patents registered in USPTO or EPO. While this share may sound small, with the global nanotechnology market estimated at USD 39.2 billion in 2016 and a projected CAGR of 18% from 2016 to 2021[11] , the future of industrial applications of nanotechnology is promising, and the technological revolution that nanoscience started in many industry sectors will continue.■

1. See https://www.reportlinker.com/p04539093/Global-and-China-Graphene-Industry-Report.html?utm_source=PRN and http://www.chinadaily.com.cn/cndy/2018-02/01/content_35623375.htm
2. See https://www.alliedmarketresearch.com/nano-materials-market (produced 2016)
3. See Brent L. Nannenga, Guanhong Bu and Dan Shi. The Evolution and the Advantages of MicroED. *Front. Mol. Biosci*., 12 December 2018.
4. See Duyvesteyn et. al. Machining protein microcrystals for structure determination by electron diffraction. PNAS, 115 (38): 9569-9573(2018)
5. See Gabriel A. Silva. A new frontier: The convergence of nanotechnology, brain machine interfaces, and artificial intelligence. *Front. Neurosci.*, 16 November 2018. https://doi.org/10.3389/fnins.2018.00843
6. See Li et. Al. A DNA nanorobot functions as a cancer therapeutic in response to a molecular trigger in vivo. *Nature Biotechnology*, 36, 258-264 (2018)
7. See https://www.nature.com/articles/nmeth.3969
8. See https://www.bccresearch.com/market-research/nanotechnology/nanotechnology-in-energy-applications.html
9. See https://statnano.com/news/62082
10. See https://statnano.com/report/s140
11. See https://www.bccresearch.com/market-research/nanotechnology/nanotechnology-market-products-applications-report.html

GREAT EXPECTATIONS

The United Nations' 17 Sustainable Development Goals (SDG) for 2030 are a roadmap to a better, more sustainable future. Nanotechnology could significantly increase sustainable development in the energy, water, chemical, medical and pharmaceutical sectors, according to the 2016 Global Sustainable Development Report[1].

Nanoscience and technology could contribute to achieving SDGs on safe drinking water; strengthening food security; health; environmental protection; energy storage, production, and conversion; and manufacturing, according to Michiko Enomoto, the head of the Asian and Pacific Centre for Transfer of Technology of the United Nations Economic and Social Commission for Asia and the Pacific[2].

Some of the technologies and nanomaterials highlighted in the 2016 Global Sustainable Development Report, such as nanostructured solar cells, organic and inorganic nanomaterials, such as graphene, carbon nanotubes, and others, have been discussed at length in this report.

We have taken you on a bibliographic journey through the nanoscale. From the beginning of the field to where experts believe it should go.

Nanoscience output, according to data from Dimensions, has grown by more than 130-fold in the last 30 years. The fastest growth in the field, a CAGR of 27%, was seen between 2000 and 2010, driven by important breakthroughs, such as the growth of crystalline semiconductor nanowires, the invention of electronic ink, and the isolation of graphene sheets.

Publication data also reveals that nanoscience is becoming increasingly interdisciplinary. Nanoscience output contributes to publications in many subject areas, extending beyond physical science fields like chemistry and material sciences. The proportion of nanoscience in the total output of life sciences is consistently growing according to data from the Nature Index.

In a cross-country comparison, using data from Dimensions, we found that from 1990 to 2018 China was the fastest-growing producer of nanotechnology research, with a CAGR of 36%. China overtook the US in 2018, to become not only the largest producer of nanotechnology research, but also of high-quality nanotechnology research as measured by the Nature Index. Accordingly, more than half the top 10 producers of high-quality nanotechnology research are Chinese institutions, with the Chinese Academy of Science (CAS) producing the largest amount of high-quality nanotechnology articles as measured by the Nature Index.

Looking closer at nanomaterials using Springer Nature's Nano database, we found that nanoparticles were the most popular nanostructure studied, based on the number of research articles, between 2010 and 2018. Popular nanostructures in patent applications for that period include nanoparticles, graphene, quantum dots, nanowires and nanocrystals. Research articles between 2010 and 2018 focussed on the following nanomaterial applications: electronics, catalysis, drug delivery, optoelectronics, and energy storage, many of which were also popular applications, according to patent data.

We interviewed experts about the current state of their fields and existing challenges. Goals included, creating nanodevices capable of meeting the increasing demand for high-performance computing and data storage; the development of 'green' nanomaterials; the production of nanomaterials in commercially viable amounts; converting waste carbon dioxide into useful products; and studying the toxicity of nanodrugs, and educating the public about them. More broadly, experts identified the need to exercise a greater level of control over reproducibility, structure, particle size, stability, cost, sustainability and scalability, as well as translating research results into applications.

Experts also noted that more studies are needed to evaluate the long-term impact of nanomaterials and technologies on the environment. They urged the need for industry, market and governmental forces to work together to promote the development of green nanotechnology. They also noted that appropriate legal regulations need to be developed to keep up with new advances, such as smart nanomedical technologies.

China, a nanotechnology leader, thanks to strategic planning and sustained funding from the government, will no doubt be a significant contributor. Interviewed experts mostly agreed that China is already a leading contributor to nanotechnology research output, either in synthesis of nanomaterials, development of nanoelectronic devices, nanomaterials for energy conversion and storage, nanomedicine, or the use of green nanomaterials. Turning these research results into disruptive technologies for industrial use is the next step needed for China to further grow its nanotechnology.

Nanotechnology's contribution to the world's economy is expected to exceed USD 125 billion by 2024[3]. With the integration with AI technology, opportunities for nanotechnology are further expanding. It could play an important role in sustainable agriculture, smart cities, and digital living. With cautious management of its development, nanotechnology can be harnessed to change lives and improve the environment. ■

1. See https://sustainabledevelopment.un.org/content/documents/10789Chapter3_GSDR2016.pdf
2. See her presentation slides at http://apctt.org/sites/default/files/Ms.%20Michiko%20Enomoto.pdf
3. See https://www.researchandmarkets.com/reports/4520812/global-nanotechnology-market-by-component-and

Appendix | Methodology and Nature Index data

This report uses both quantitative analysis and qualitative information to paint a picture of the current landscape of nanoscience and technology research, highlighting its importance to the development of basic sciences and industrial applications.

The quantitative analysis uses bibliographic data from Dimensions, Nature Index, and the Nano database developed by Digital Science and Springer Nature. Specifically, to examine the contribution to basic sciences by nanoscience and technology, a key word search using "nano" is applied to primary research articles published from 2012 to 2018 in the 82 high-quality science journals tracked by Nature Index. This resulted in 66,991 nano-related papers, defined as any articles that use "nano" in the abstract, title or full text of the article.

The journals included in the Nature Index are selected by a panel of active scientists, independent of Nature Research. The selected journals represent about 5% of journal articles in natural sciences, but account for close to 30% of total citations to natural science journals. The Nature Index categorizes journals into four broad research fields: chemistry, physical sciences, and life sciences, and earth and environmental sciences.

This report follows the existing journal groups of Nature Index to categorize primary research articles in chemistry, physical sciences and life sciences. Journal titles covered in these three subject areas are listed below. Furthermore, all primary research articles in *Nature Materials*, *Advanced Materials*, *Advanced Functional Materials* and *Macromolecules* are defined as in material sciences, along with selected articles in other journals tracked by Nature Index, using a set of field of research codes (FoRs). Note that some articles can sit in more than one of the four broad research fields.

For the country comparison of nanoscience research output, Nature Index article count (AC) and fractional count (FC) are used. AC is calculated where a count of one is assigned to an institution or country if one or more authors of the research article are from that institution or country, regardless of how many co-authors there are from outside that institution or country; while FC takes into account the percentage of authors from that institution (or country) and the number of affiliated institutions per article. For calculation of the FC, all authors are considered to have contributed equally to the article. The maximum combined FC for any article is 1.

Furthermore, qualitative data are collected from individual interviews with nanoscience experts from China and elsewhere for insights about challenges and opportunities in the development of nanoscience and technology. Interviews were conducted by phone or via email.

Subjects	Journals
Chemistry	*Advanced Materials; Analytical Chemistry; Angewandte Chemie International Edition; Chemical Communications; Chemical Science; Inorganic Chemistry; Journal of the American Chemical Society; Macromolecules; Nano Letters;Nature* (only articles classified in this subject area)*; Nature Chemical Biology; Nature Chemistry; Nature Communications* (only articles classified in this subject area)*; Nature Materials; Nature Nanotechnology; Organic Letters; PNAS* (only articles classified in this subject area)*; Science* (only articles classified in this subject area); *Science Advances* (only articles classified in this subject area)*; The Journal of Physical Chemistry Letters.*
Physical Sciences	*ACS Nano; Advanced Functional Materials; Advanced Materials; Applied Physics Letters; Astronomy & Astrophysics; European Physical Journal C; Journal of High Energy Physics; Monthly Notices of the Royal Astronomical Society: Letters; Nano Letters; Nature* (only articles classified in this subject area)*; Nature Communications* (only articles classified in this subject area)*; Nature Materials; Nature Nanotechnology; Nature Photonics; Nature Physics; Physical Review A; Physical Review B; Physical Review D; Physical Review Letters; Physical Review X PNAS* (only articles classified in this subject area)*; Science* (only articles classified in this subject area)*; Science Advances* (only articles classified in this subject area)*; The Astrophysical Journal Letters.*
Life Sciences	*Life Sciences; American Journal of Human Genetics; Cancer Cell; Cancer Research; Cell; Cell Host & Microbe ;Cell Metabolism; Cell Stem Cell; Current Biology; Developmental Cell; Ecology Letters; eLife; Genes & Development; Genome Research; Immunity; Journal of Biological Chemistry; Journal of Cell Biology; Journal of Clinical Investigation; Journal of Experimental Medicine; Journal of Neuroscience; Molecular Cell; Molecular Psychiatry; Nature* (only articles classified in this subject area)*; Nature Biotechnology; Nature Cell Biology; Nature Chemical Biology; Nature Communications* (only articles classified in this subject area)*; Nature Genetics; Nature Immunology; Nature Medicine; Nature Methods; Nature Neuroscience; Nature Structural & Molecular Biology; Neuron; PLOS Biology; PLOS Genetics; PNAS* (only articles classified in this subject area)*; Proceedings of the Royal Society B; Science* (only articles classified in this subject area)*; Science Advances* (only articles classified in this subject area)*; Science Translational Medicine; The EMBO Journal; The ISME Journal: Multidisciplinary Journal of Microbial Ecology; The Plant Cell.*

National Center for Nanoscience and Technology, China

The National Center for Nanoscience and Technology, China (NCNST) was established in 2003 by the Chinese Academy of Science (CAS) and the Ministry of Education as an institution dedicated to fundamental and applied research in the field of nanoscience and technology, especially those with important potential applications. Under the supervision of its governing board NCNST aims to become a world-class research centre, as well as public technological platform and talent training centre, and to act as an important bridge for international academic exchange and collaboration.

The NCNST has three CAS Key Laboratories: the CAS Key Laboratory for Biological Effects of Nanomaterials & Nanosafety, the CAS Key Laboratory for Standardization & Measurement for Nanotechnology, and the CAS Key Laboratory for Nanosystem and Hierarchical Fabrication. Besides, there are three public platforms: Laboratory of Theoretical and Computational Nanoscience, Nanofabrication Laboratory, and Division of Nanotechnology Development. The NCNST has also co-founded 19 collaborative laboratories with Tsinghua University, Peking University, and CAS.

The NCNST has doctoral and postdoctoral education programmes in condensed matter physics, physical chemistry, materials science, and nanoscience and technology. By the end of 2018, 2,299 peer-reviewed papers were published, and a total of 1,230 patents applied for, of which 568 have been authorized. In 2014, the International Evaluation Committee lauded the significant achievements and outstanding contributions in nanoscience, and remarked that NCNST had risen to a position of "by far the best in China". In 2018, the Nature Index showed that NCNST has become one of CAS's top five institutes.

In October 2015, CAS set up the Center for Excellence in Nanoscience (CAS-CENano) to accelerate the establishment of a new model for scientific research. It aims to gather innovative talent, focus on the frontier of nanoscience, to achieve major breakthroughs and become an internationally renowned organization.

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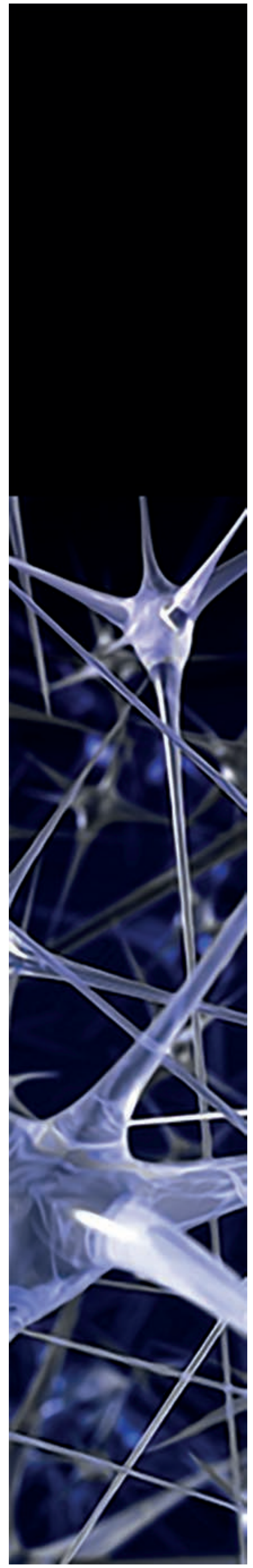

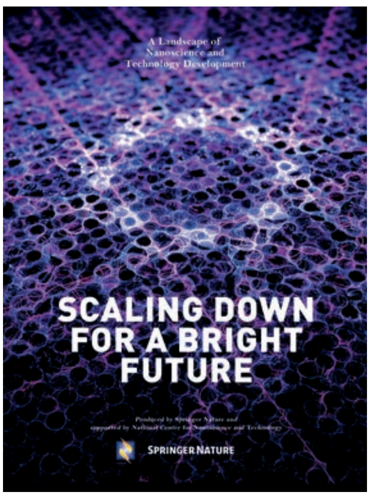

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