CAS INSIGHTS™

NANOMATERIALS

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Introduction

Interest in nanomaterials is growing due to their numerous applications across many sectors. We conducted a comprehensive analysis of the CAS Content Collection™ to better understand the emerging trends and latest research and development in nanomaterials. The CAS Content Collection is the largest human-curated collection of published scientific knowledge, with over one million documents related to nanomaterials published since 2019. Based on our findings, topics of research or commercial interest were selected for further analysis, in which we examined all relevant journal articles and patent documents published over the last two decades to gain further insight into each nanomaterial-related field.

Emerging topics in nanomaterials

To identify and understand the most active areas of R&D within the broad landscape of nanomaterials, we adopted a three-pronged approach:

1. We conducted a quantitative journal and patent document data analysis to build conceptual mind maps showing a hierarchy of active and emerging research concepts.
2. We then selected key features (concepts) in the mind maps, focusing on examples of the most influential research driving their emergence with recent literature examples.
3. Finally, we performed an additional quantitative analysis to explore connections between concepts in the mind map.

The conceptual mind maps were created by identifying and analyzing 1.3 million nanomaterial-related published journal and patent documents in the CAS Content Collection since 2019. We used Natural Language Processing analysis, guided by subject matter experts, to extract and group scientific concepts from these documents. To help select relevant topics in the map, we calculated the publication frequency and growth rate since 2019 for each concept. This allowed us to establish a hierarchy of concepts and categorize each according to whether they fell under 'Applications' or 'Materials'.

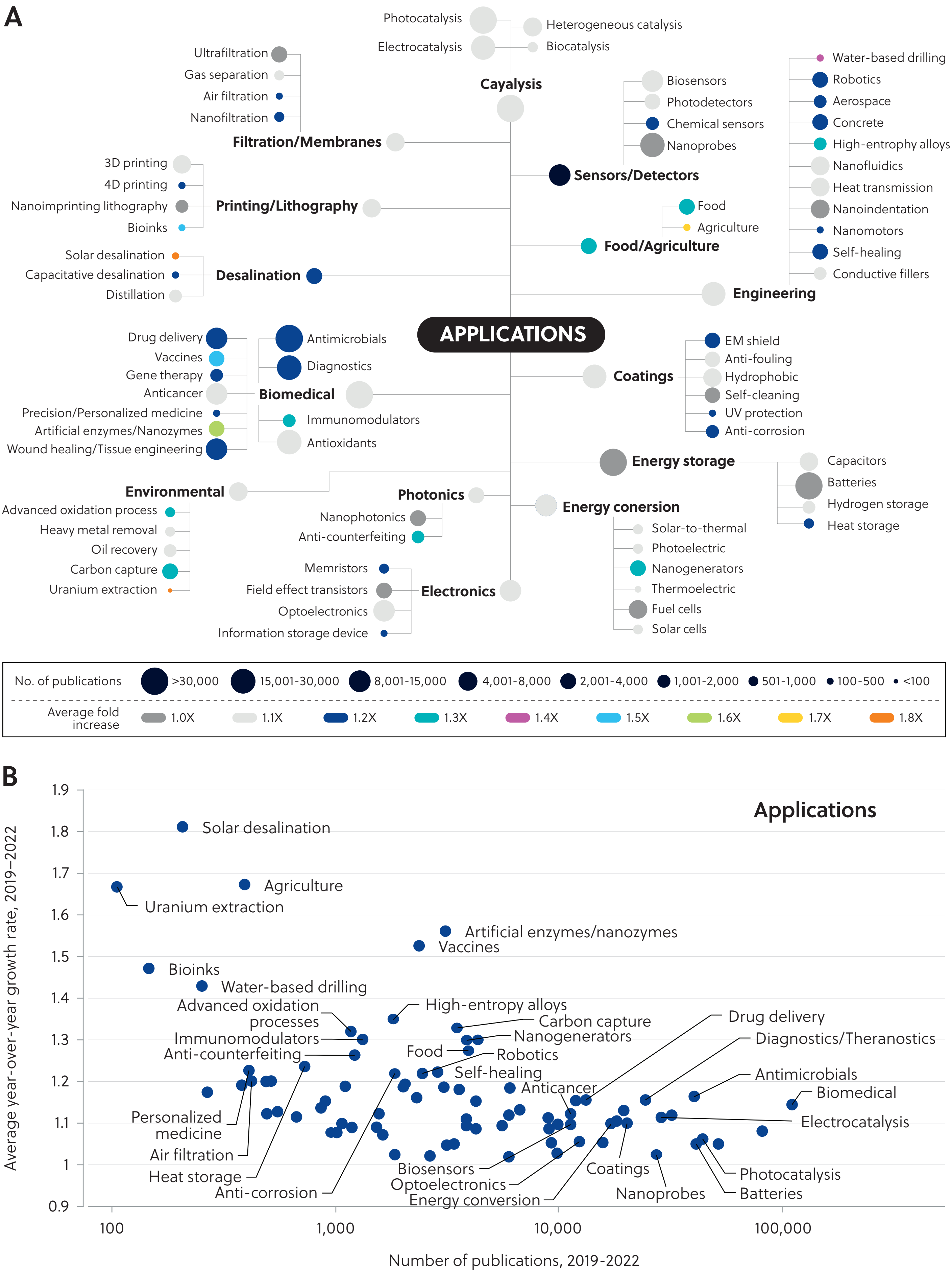


Figure 1. (A) Conceptual mind map and (B) Average 2019–2022 growth rate versus number of publications over that time period that reference applications involving nanoscale materials.

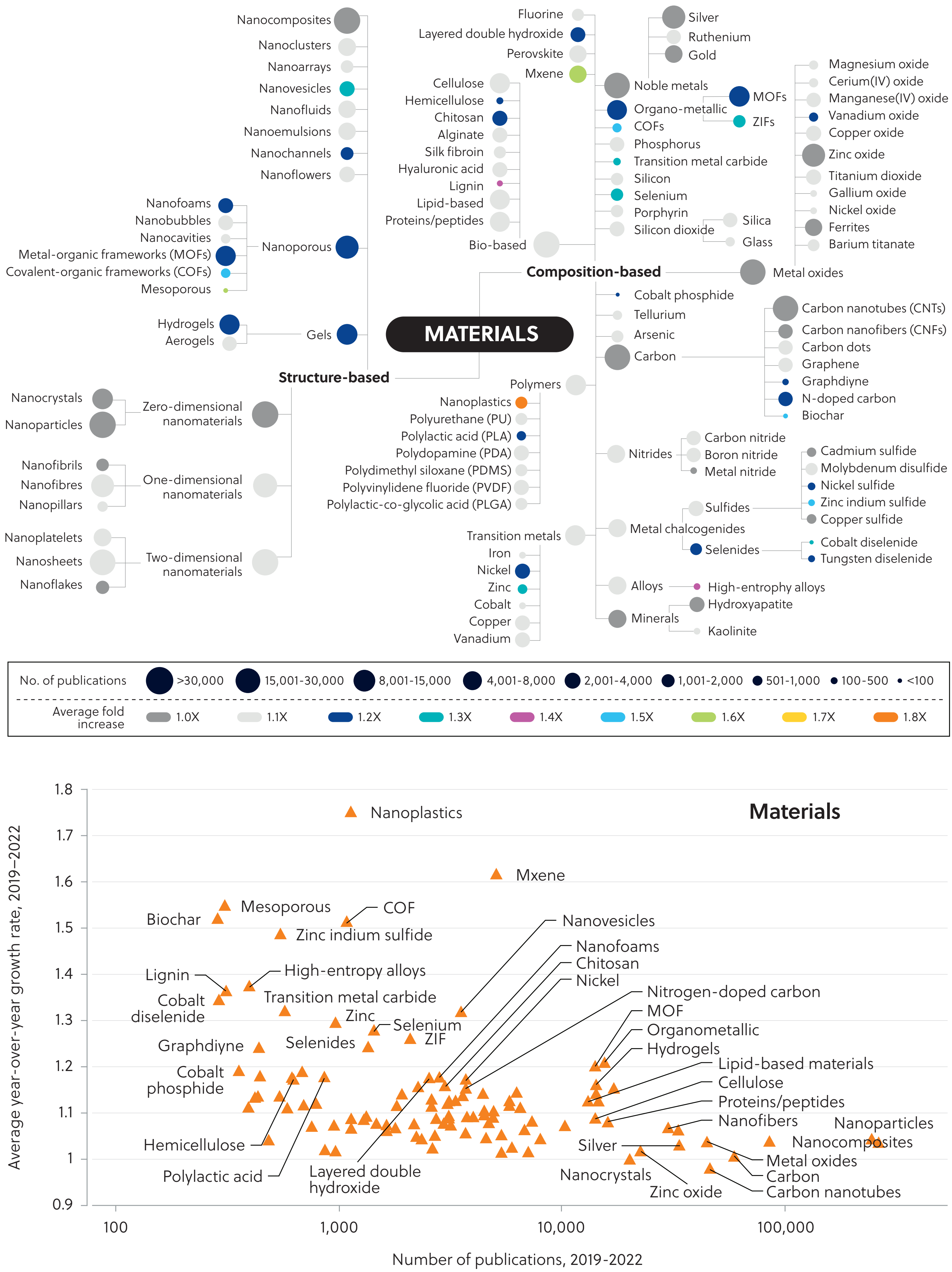


Figure 2. (A) Conceptual mind map and (B) Average 2019–2022 growth rate versus absolute number of publications that reference nanoscale materials.

In the Applications section of the map (**Figure 1**), the most prominent emerging fields — shown as branches — are biomedical (driven largely by diagnostics, antimicrobials, antioxidants, and drug delivery), catalysis (electro and photocatalysis), and energy storage. In the materials section (**Figure 2**), active research areas include 0D and 2D nanomaterials, carbon-based materials, naturally derived materials (including cellulose and lipids), and noble metals. In the sections below, we will highlight concepts within each mind map of high growth between 2019–2022.

Trends in applications

There are several emerging applications in nanoscience, notable for their relative growth rate and the related publications in which they appear from 2019–2022.

Nanogenerators, specifically triboelectric and piezoelectric nanogenerators, generate electrical energy from motion. Their growing frequency in publications appears to be driven by their use to power wearable devices such as human motion sensors[1,2] and in human-machine interfaces.[3] The emerging materials most prominently associated with nanogenerators include nanofibers[4] and zinc oxide,[5] with hydrogel usage also growing quickly.

Studies focused on decreasing carbon dioxide (CO_2) levels in the atmosphere (aiming to capture and store/convert it before release) are important due its impact on global warming. The use of nanomaterials in CO_2 sequestration has grown in recent years since catalyst surface area and porous nature play significant roles in CO_2 capture and conversion. More than 90% of the studies involving nanomaterials use them as catalysts for reducing CO_2 to synthesize useful chemicals, followed by capturing and storing them using nanoporous materials.

Sustainable agriculture and nanofertilizers have the second highest growth rate in the applications category and co-occur primarily with nanoparticles.[6–8] Nanomaterials have gained traction as possible ways to address the world's food security and agricultural challenges, such as those caused by pesticides, traditional fertilizers, climate change, irrigation difficulties, and poor soil quality. They are also considered a possible pathway to sustainable fertilizers[9] and agriculture.[10]

Life science and biomedical applications have driven a significant amount of growth in the use of nanomaterials, as shown in **Figure 1A**. Three examples of note include vaccines, nanozymes, and bioinks.

Nanoparticle-based vaccines are an emerging research area that uses nanotechnology to enhance the effectiveness of vaccines.[11–13] In these vaccines, nanoparticles, liposomes, nanogels, micelles, and dendrimers are employed as delivery vehicles for antigens and adjuvants, aiming to improve immune responses and vaccine efficacy.[14,15] Nanovaccines can help advance targeted delivery, antigen presentation, stimulation of innate immunity, and elicit a robust T-cell response, which can help combat various infectious diseases. Moreover, nanovaccines can be valuable in generating effective immunotherapeutic formulations against cancer.[16,17]

Nanozymes are nanomaterials with enzyme-like catalytic activities.[18,19] These synthetic nanostructures mimic the functions of natural enzymes but offer several advantages, such as better stability, tunable catalytic properties, cost-effectiveness, and easier large-scale production.[20]

Nanomaterials in bioinks are also gaining popularity across many potential applications. For instance, nanomaterials can confer bioactive properties such as drug delivery capacity and antimicrobial effect to bioinks;[21] incorporating nanoparticles loaded with growth factors can promote angiogenesis and osteogenesis within printed constructs;[22–24] adding luminescent optical sensor nanoparticles can help in imaging cells;[24] and nanoparticle-containing bioinks can also be used for printing 3D organs.[25]

Trends in materials

The term 'nanoplastics' has been growing in use since 2019. Nanoplastics are synthetic or modified natural polymers typically defined as 1 μm or less in size, though some define them as between 1 to <100 nm.[26,27] These plastics have three ways of coming to be: intentional production for diverse applications, generation during the manufacturing of polymers, or through fragmentation of larger plastics.[28–30] Nanoplastic-related terms co-occur with topics like toxicity,[16,17] antioxidants, and characterization/x-ray diffraction.[31–40] These associations are mostly due to concerns about the effects of nanoplastic litter on the environment.

MXenes are a class of inorganic 2D materials that have been the subject of growing research interest since they were first reported in 2011.[41] Prominent applications of MXenes currently include electrocatalysis,[42–44] photocatalysis,[45,46] and batteries.[47,48] MXenes are well suited for use in these applications due to their high surface area, electrical conductivity, and a high degree of versatility through alteration of their surface functionality and/or combining them with other nanoscale materials. Antimicrobial applications represent an especially fast-growing area of use for the specific MXene $Ti_3C_2T_x$.[49,50] MXenes are also frequently combined with other nanoscale materials, such as carbon nanotubes (CNTs), to fully leverage their unique properties.

Covalent organic frameworks (COFs) are 2D or 3D porous polymeric networks made of one or more covalently bonded monomers. COFs can be designed to be stable and insoluble under various operating conditions.[51] It is also possible to customize the chemical or catalytic properties and pore size of COFs through the choice of the appropriate monomer(s).[52,53] COFs have utility in heterogeneous catalysis that is usually dominated by inorganic materials, as they are able to bridge the gap with homogeneous catalysis due to their customizability, which has historically only been possible with homogeneous catalysis.

Zinc indium sulfide, or indium zinc sulfide, is a ternary metal chalcogenide with a layered structure. It is a semiconductor with a bandgap of 2.2 eV and has recently attracted interest in photocatalytic and photoelectrochemical applications.[54] According to data from the CAS Content Collection, nearly 93% of the publications related to nanostructured $ZnIn_2S_4$ reference photocatalytic or photoelectrochemical applications, including water splitting,[55] CO_2 reduction[56] and removal,[57] or the degradation[58] of pollutants in aqueous media. However, the widespread application of $ZnIn_2S_4$ is hindered by the high recombination of the photogenerated charge carriers and its limited absorption in the visible region only until 563 nm.[59,60]

Notably, two naturally derived materials appear in **Figure 2**. The first is lignin, a complex organic polymer found in plant cell walls essential for providing structural support and rigidity. Its abundance and biodegradability make it an attractive material for nanoscience-related applications.[61,62] Lignin nanoparticles can serve as drug delivery carriers by encapsulating pharmaceutical ingredients and can also be incorporated into polymer matrices to create nanocomposites, which can be used in packaging and automotives. These can also be used for environmental remediation, including soil remediation, wastewater treatment, and sustainable agricultural applications.[63,64]

The second naturally derived material is biochar, made through biomass pyrolysis. Its most prominent application is in removing pollutants from water, including heavy metals[65] and organics.[66]

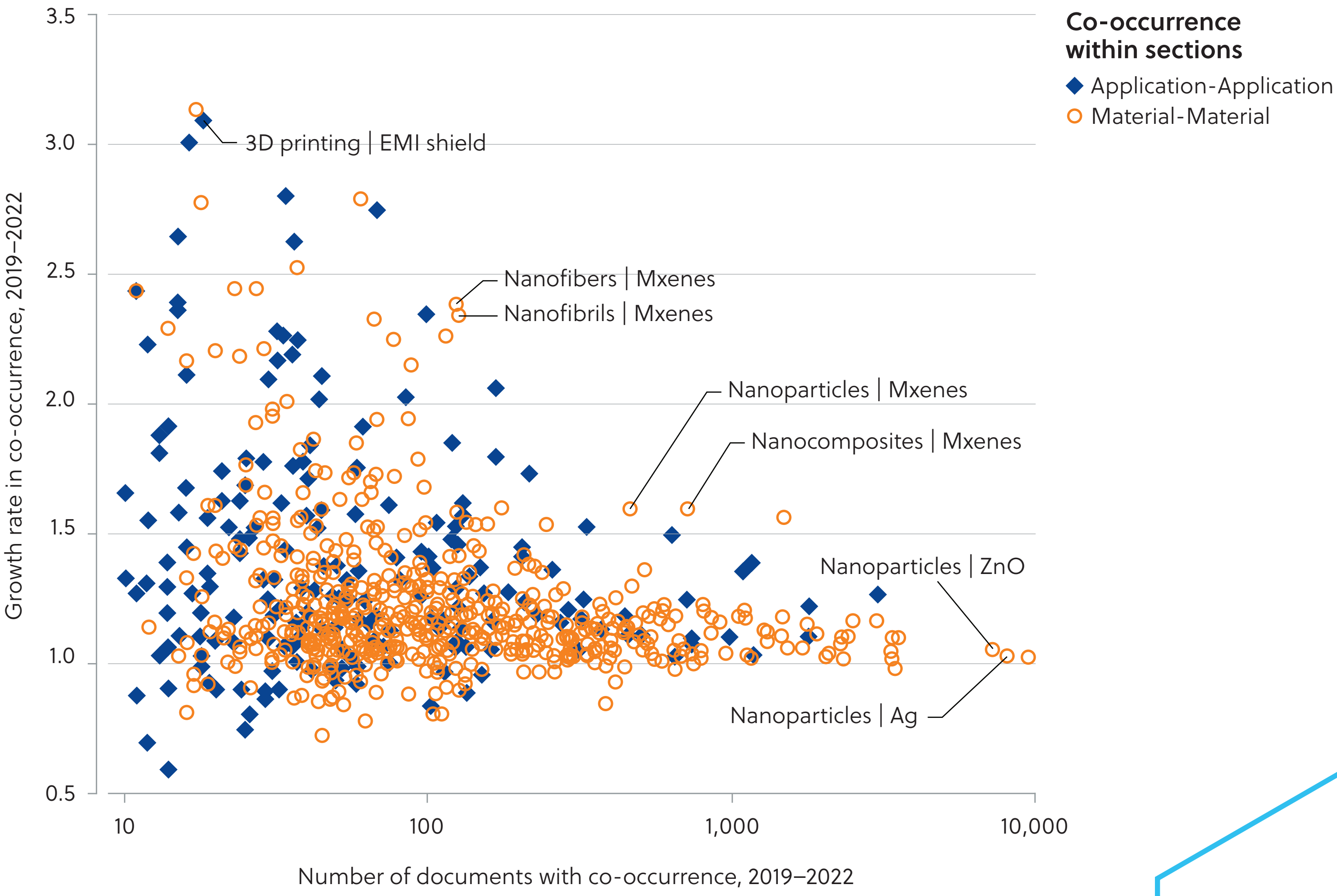
Extracellular vesicles, which represent a route of intercellular communication and are involved in essential physiological processes, have emerged as powerful tools in various fields, including drug delivery, diagnostics, and biotechnology.[67] However, the limited targeting ability of exosomes, insufficient production yield, and low drug encapsulating capabilities have hampered their clinical development. Therefore, engineering multifunctional hybrid nanovesicles that mimic natural extracellular vesicles but with favorable adaptability and flexibility has become a key challenge in expanding their application.[68–70]

Connections between concepts in nanomaterials

The plots in **Figure 3** show the average number of documents published between 2019–2022 where pairs of terms co-occur in the same sentence (x-axis) and the average growth rate of documents with those co-occurrences over the same time period (y-axis). For clarity, combinations are separated into two figures, showing the co-occurrence of concepts within the same maps (i.e., terms that appear in the application map or the materials map) and the co-occurrence of terms in different maps. The general trend observed in these data is a wide range of growth rates for combinations with relatively low publication frequency (below roughly 20–30 documents per year), with a long tail extending to high publication numbers but relatively low growth rates.

Looking at the co-occurrence of terms within the same sections (**Figure 3A**), ZnO and Ag, for example, both co-occur in proximity to nanoparticle terms in over 2,000 documents between 2019–2022 and therefore appear to be well-established nanoparticle materials. In contrast, the combination of MXenes with nanofibers and nanoparticles represents a faster-growing area of research but with fewer overall publications. Within these combinations, there are more publications with MXenes combined with nanoparticles than with the combination of MXenes with nanofibers, which is growing more quickly but with fewer overall references.

In **Figure 3B**, we can see that the combination of vaccines and lipid-based materials appears prominently, with an exceptionally high growth rate given the total number of references for this combination, which is most likely due to the large number of publications related to COVID-19 vaccines published between 2021–2022. Other biomedical applications (e.g., anticancer-nanoemulsions, vaccines, nanoparticles, and antimicrobial nanomaterials) appear prominently in this analysis, along with energy conversion, catalysis, and electromagnetic interference (EMI) shielding combinations.



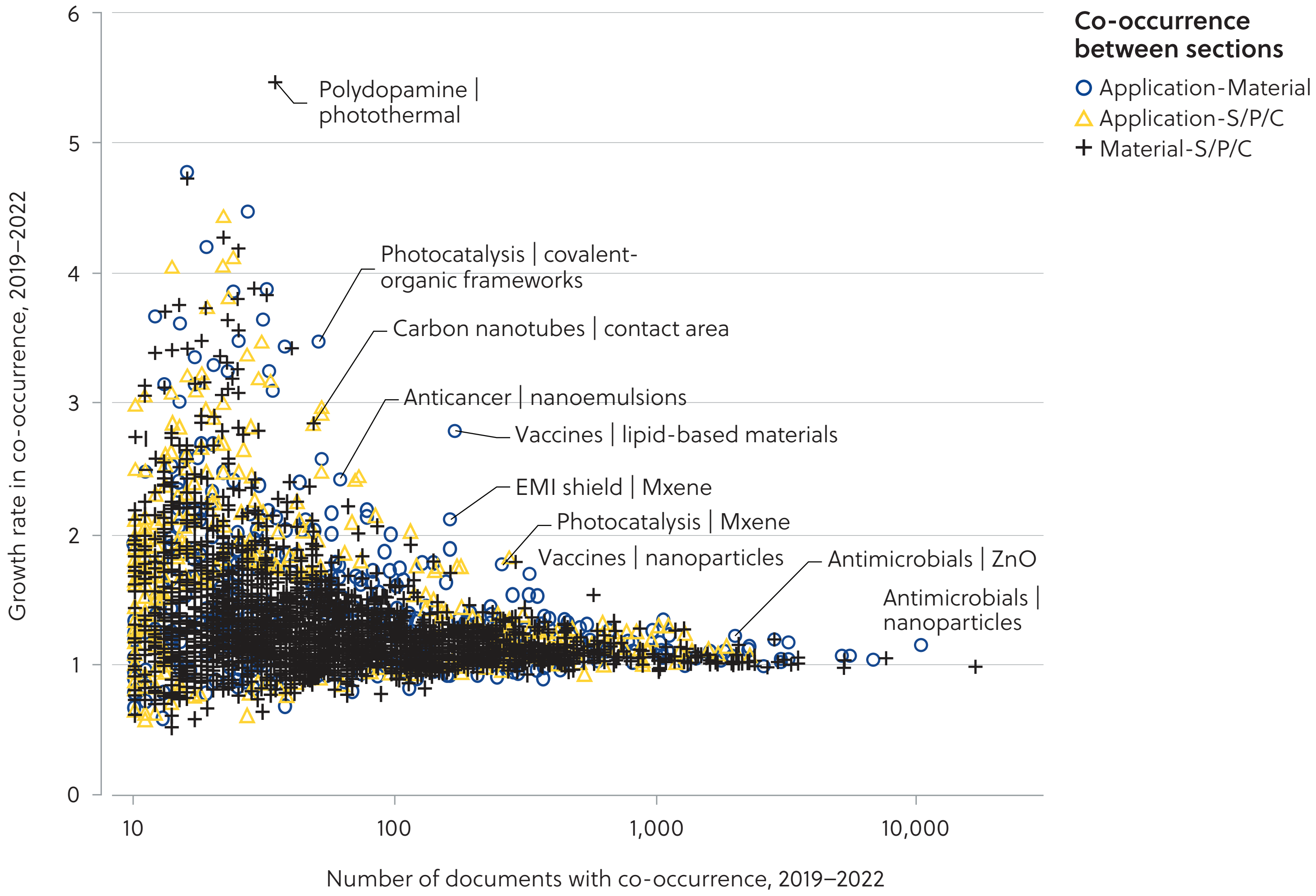


Figure 3. Average year-over-year growth rate versus absolute number of publications from 2019–2022 for concepts co-occuring in the same sentence in journal abstracts for concepts (A) in the same mind map and (B) in different mind maps.

Summary

- Analysis of 1.3 million journal/patent publications since 2019 reveals that biomedicine, catalysis, and energy storage are the most prominent emerging branches in nanomaterial applications.
- Active areas of research in materials include 0D and 2D nanomaterials, carbon-based materials, naturally derived materials such as cellulose, lipids, and noble metals.
- The combination of MXenes with nanofibers and nanoparticles is a fast-growing area of research, as is the combination of vaccines and lipid-based materials.

Nanoscale materials in energy-related applications

Global energy consumption is rising, particularly in countries with growing populations and incomes.[71] Nanotechnology and nanomaterials are considered part of the solution to satisfy rising energy demands while lowering greenhouse gas emissions. Nanotechnology can help improve the efficiency of energy use, energy production, energy storage, and energy transmission.[72–75] Nanoscale materials have also been used in many renewable energy applications.[76,77]

The top ten areas of focus for the application of nanoscience and nanomaterials about energy were identified and categorized as follows:

1. Batteries
2. Solar/photovoltaic cells
3. Supercapacitors
4. Water splitting
5. Hydrogen storage
6. Fuel cells
7. Thermoelectric generators
8. Triboelectric generators
9. Thermal energy storage
10. Solar thermal systems

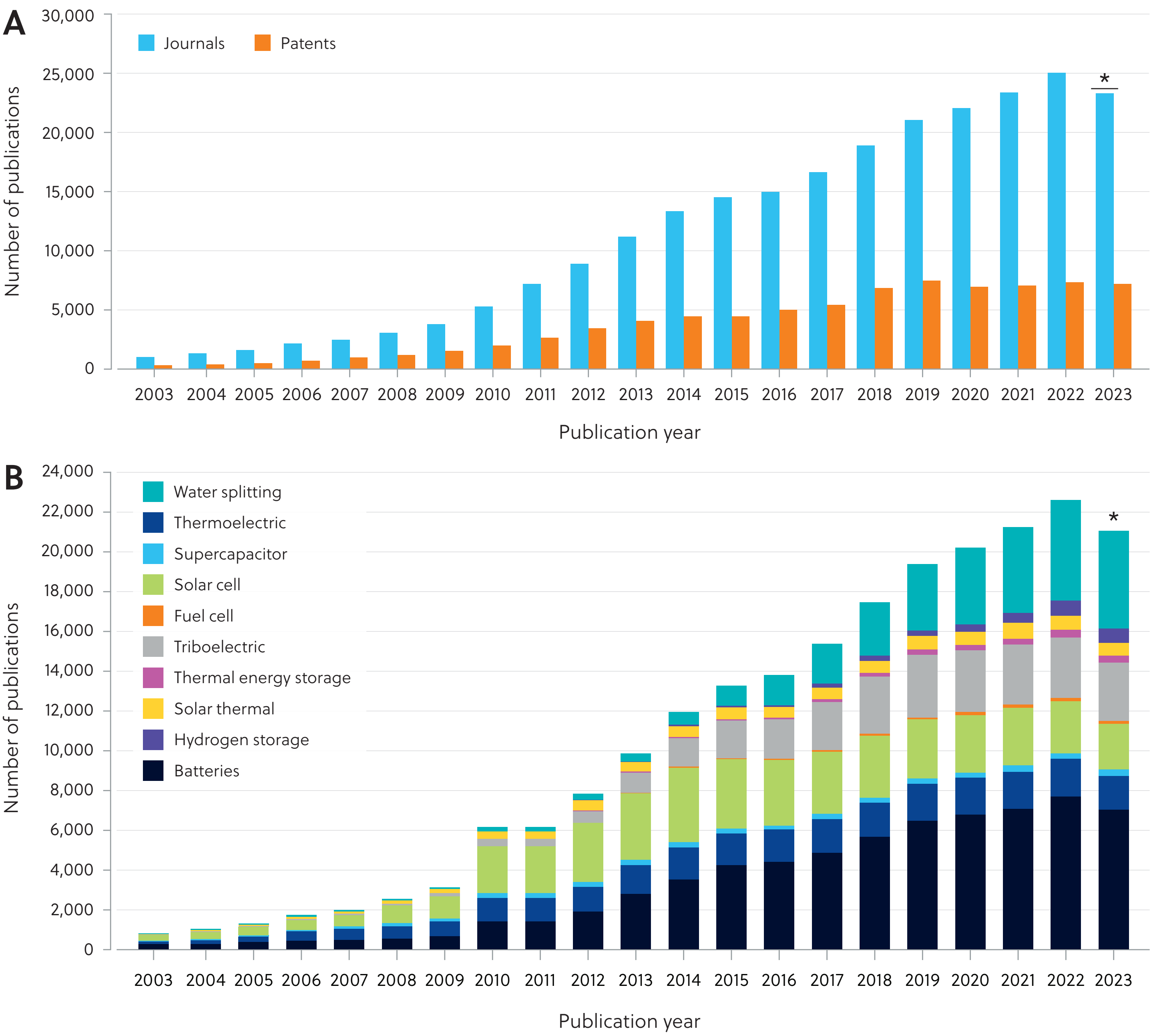
Publication trends

Figure 4A shows the frequency of journal and patent publications containing energy applications of nanomaterials. Journal publications have grown steadily since 2003, reaching roughly 25,000 per year in 2023. Patent publications have also grown over that time, but to a lesser degree.

Research organizations in China, notably the Chinese Academy of Sciences, have published the highest number of research articles. This is a recurring theme, partly due to the size of the Chinese Academy of Sciences, an umbrella organization consisting of 124 institutions. The average number of citations per publication can also be used as a rough indication of the impact of research organizations on the field. The top three organizations by this measure are Stanford University in the U.S., École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland, and the University of Adelaide in Australia.

The 15 commercial entities with the highest number of patents assigned in this area are in China, South Korea (notably LG Chem and Samsung SDI), the U.S., and Japan. For non-commercial organizations, China again dominates the field, with the Chinese Academy of Sciences having more than triple the number of patents between 2003–2023 as the next highest-ranked organization.

Much of the overall growth in publications in the area of nanomaterials in energy (**Figure 4**) was due to the research interest in batteries, solar cells, and fuel cells during the first ten years, with interest in supercapacitors and water splitting driving the number of publications from 2013 onward. The main driver behind the growth in patent publications was again the batteries sector, whose publication number and frequency rose consistently until 2019, declined in 2020–2021, and then rose again from 2022 onwards.



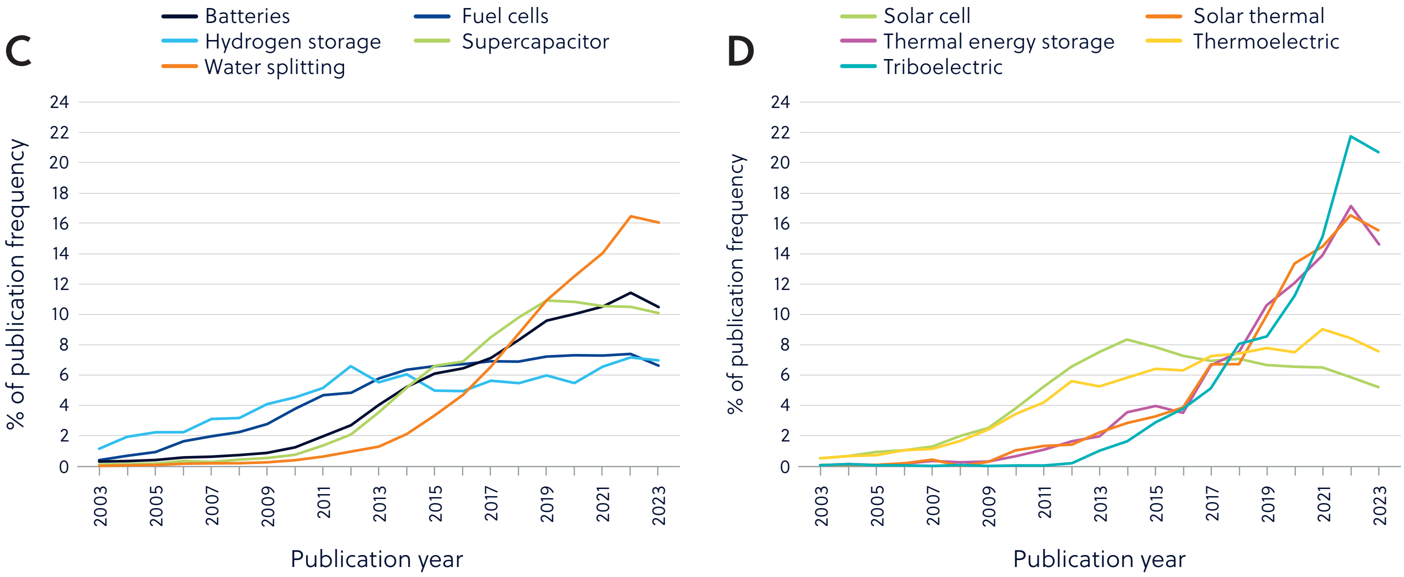


Figure 4. (A) Publication trends on the topic of energy in association with nanoscience-related research over the last two decades. Data includes journal and patent publications from the CAS Content Collection from 2003–2023. *The Year 2023 has incomplete data due to the date of data acquisition. (B) Number of journal publications by energy application category from 2003–2023. (C) and (D) Normalized publication frequency for journal publications by year from 2003–2023 by application category.

Regarding the total number of publications, it is no surprise that batteries are the dominant energy application, given the rise in demand for electric vehicles[79] and stationary storage of renewable energy (**Figure 5**).[80] The total number of battery publications is almost twice as high as that of the next application, solar cells, which emphasizes the interest in green energy.

The top seven battery chemistries using nanoscale materials are Li-ion, Na-ion, Li-S, Zn-air, Zn-ion, Al-ion, and K-ion. When comparing the number of patents vs. journals, we observed that, though lower in total publications, Li-S has more patents than Na-ion. This higher number of patents is likely due to the high energy density of Li-S batteries, their low cost, and the natural abundance of sulfur.[81]

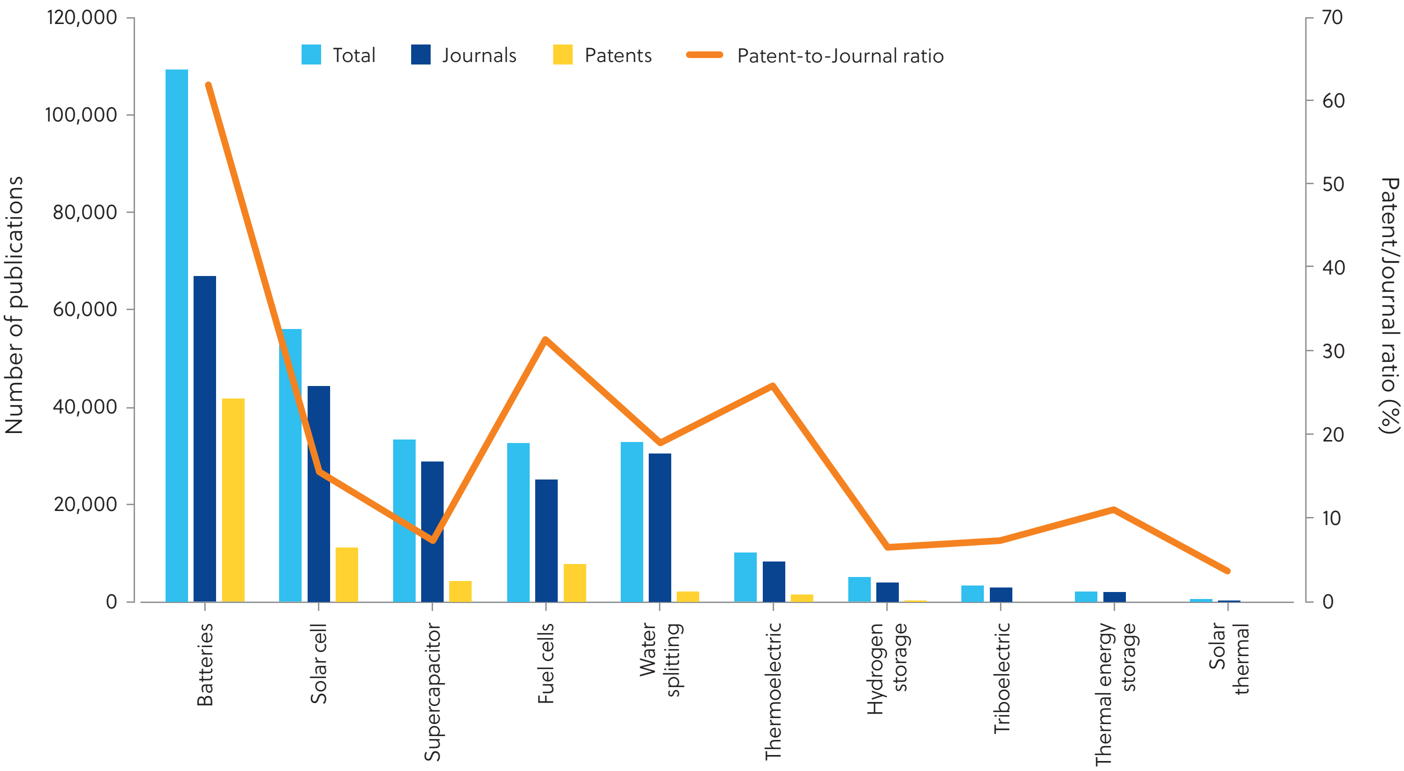


Figure 5. Total number of publications, journal publications, patent publications, and patent-to-journal ratio by energy application category from 2003–2023.

While batteries show the highest patent-to-journal ratio of the nanoscience energy topics (**Figure 5**), fuel cells and thermoelectrics are ranked second and third despite having fewer publications. There are more total patents on fuel cells than supercapacitors, suggesting that the latter has yet to mature enough for commercialization. In the case of solar cells, though they have a higher number of total patent publications than fuel cells, they have a lower patent-to-journal publication ratio, again signifying that much of the research in relation to this technology has yet to reach commercialization. The publication trends in thermoelectrics, namely a relatively high patent-to-journal ratio and low number of overall publications, suggest a somewhat lower level of general interest in this application, but more focus on commercialization.

Substance data trends in energy applications

The most commonly used nanoscale substances in almost all energy applications are carbon-based. The only exception is in solar cells, where titanium dioxide (TiO_2) is used more commonly. Examples of carbon-based nanoscale materials in energy include nanoporous carbon[82] with incorporated metals and other dopants used in batteries, supercapacitors, fuel cells, and water splitting. There are also numerous examples of 0D, 1D, and 2D carbon nanomaterials in energy applications. These include carbon nanospheres, used to support single-atom hydrogen evolution reaction catalysts in water splitting,[83] and CNTs, used in batteries and other electrochemical applications that leverage their strength, electrical conductivity, and high surface area.[84,85] CNTs are also used in triboelectric generators to improve performance through their increased surface area and electrostatic effects and in thermoelectrics.[87] Carbon nanosheets and graphene are also used in electrochemical applications, where they can be combined with other materials either directly in their atomic-level structure (by doping with metals and nonmetals)[88] or by stacking them with other materials.[89]

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Several transition metal oxides are also commonly used in supercapacitor electrodes, with manganese dioxide (MnO_2) being the most prominent nanoscale material among them[90] due to its high specific capacitance, low cost, and chemical stability. This includes the use of MnO_2 in the form of pure nanowires,[91] core-shell nanowires,[92] and nanosheets.[93]

After carbon-based materials, bismuth telluride (Bi_2Te_3) is the second-most frequently used nanoscale material in thermoelectric applications due to its uniquely high thermoelectric figure of merit (a combination of its electrical conductivity, thermal conductivity, and Seebeck coefficient).[94] The figure of merit can be increased further by using 1D forms of Bi_2Te_3, which reduces the thermal conductivity disproportionately compared to the electrical conductivity.[95] For a full quantitative breakdown of the nanoscale substances used across all applications, please refer to the full ACS Nano Nanomaterials manuscript.

The top three nanoscale forms referenced in journal and patent publications on energy applications are nanoparticles, nanotubes, and nanosheets, which account for more than 50% of all nanoscale forms. Interestingly, these are 0D, 1D, and 2D forms, indicating that all three types are used frequently.

Examining the different time trends of individual nanoscale forms, nanoflowers, nanosheets, and nanoclusters appear to be growing the fastest in journal publications. At the same time, nanoplatelets and nanoplates stand out in patent publications, suggesting growth in commercialization activity.

Figure 6 shows a breakdown of substance classes of the journal article by energy application for publications with a nanomaterial component. Reading vertically down each energy application indicates how frequently each material class is used (square size) and their relative use in journal versus patent publications.

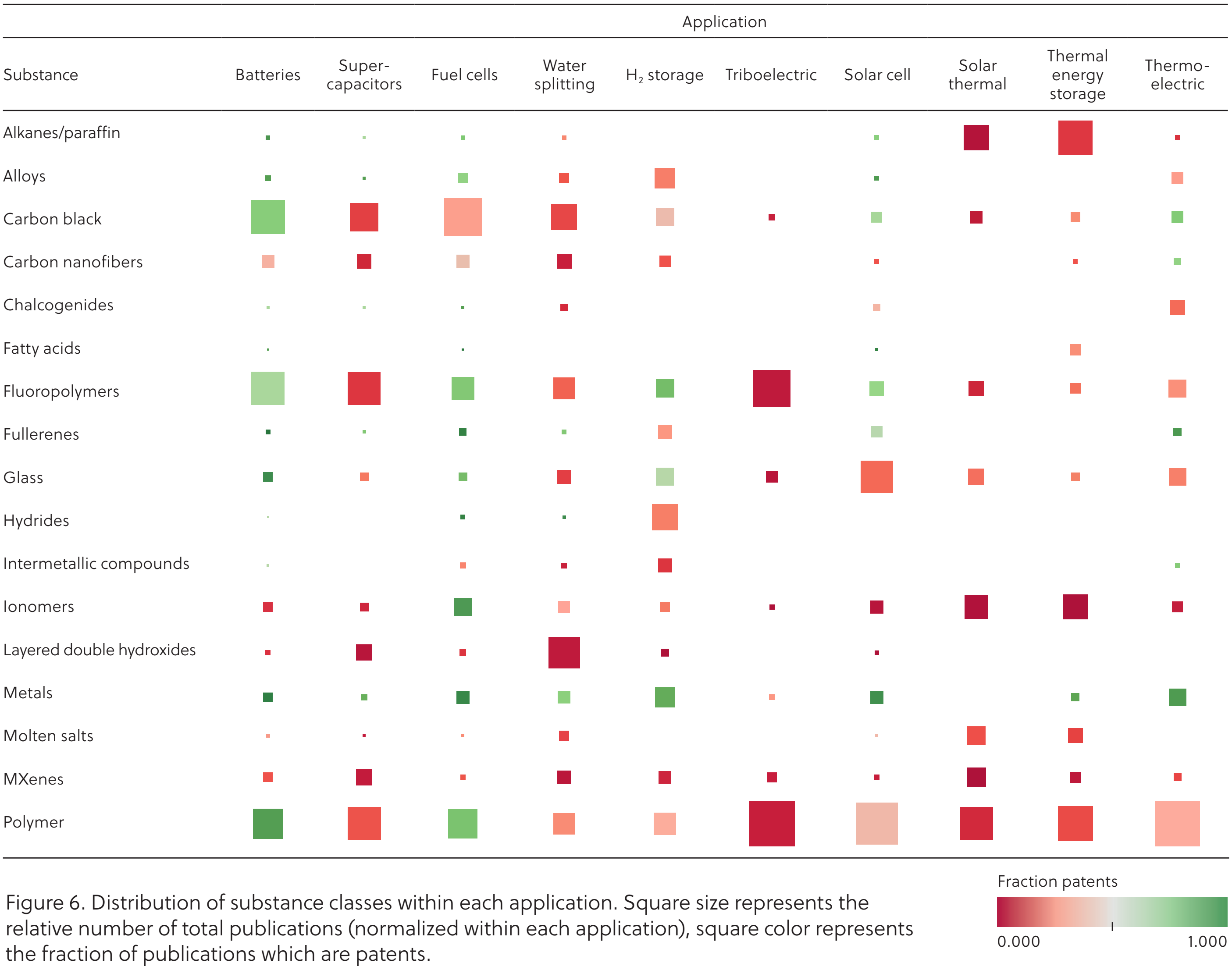

Figure 6. Distribution of substance classes within each application. Square size represents the relative number of total publications (normalized within each application), square color represents the fraction of publications which are patents.

Notable trends that can be observed in Figure 6 include the use of layered double hydroxides (LDHs) in supercapacitor electrodes, which includes the use of Ni-Co LDHs supported on reduced graphene oxide,[96] hollow spheres made of Ni-Co LDH sheets,[97] and nanowires with a core consisting of the high specific capacitance material $MgCoO_4$, or Co-Fe LDH, as the shell.[98] Porous and hollow carbon nanofibers synthesized through carbonizing electrospun polymers are also used fairly frequently in supercapacitors as electrodes,[99] or as supporting templates for other materials such as metal phosphides,[100] or even Zn-Mg-Al LDH nanosheets.[101]

MXenes have been studied in all the energy applications discussed in this section, which in part reflects the great potential of and interest in these materials. As previously discussed, this interest stems mainly from their morphology, electrical properties, and customizability. Prominent applications for MXenes in energy include supercapacitors, flexible electrodes,[102] and composite electrodes with graphene.[103] MXenes have also been used as a skeleton for phase change materials in solar thermal and thermal energy storage applications,[104,105] due to their high thermal conductivity, photothermal conversion efficiency,[106] and thermal energy storage.

Summary

- The use of nanoscale materials in energy applications saw significant, sustained growth between 2003–2023, becoming an established and expansive field.
- The more mature applications within this field include batteries, fuel cells, and photovoltaics, while growth has also been driven by new interest in applications such as triboelectric and other nanogenerators, solar thermal systems, and thermal energy storage technologies.
- Several diverse factors have motivated the use of nanoscale materials, including their strength, electrical and thermal transport properties, high surface area, and high degree of chemical and morphological customizability.
- Nanoscale materials are expected to continuously be used in existing and new energy applications.

Nanosensors

Nanosensors are devices designed at the nanoscale and can use various nanomaterials. These sophisticated devices operate at an intersection of nanotechnology, physics, and materials science. Incorporating nanomaterials such as nanoparticles, nanowires, nanotubes, or quantum dots enhances the specificity and sensitivity of sensors, enabling precise measurement.[107–110] Moreover, nanomaterials provide a high surface-area-to-volume ratio, thereby amplifying the interactions between sensor and target. In addition, they offer a cost advantage due to their miniature size.

Publication trends

The number of journal publications related to nanosensors has steadily increased over the last 20 years (**Figure 7**), doubling between 2013 and 2023. In contrast, the number of patent publications shows much more sedate growth, indicating a substantial gap between basic research and commercialization.

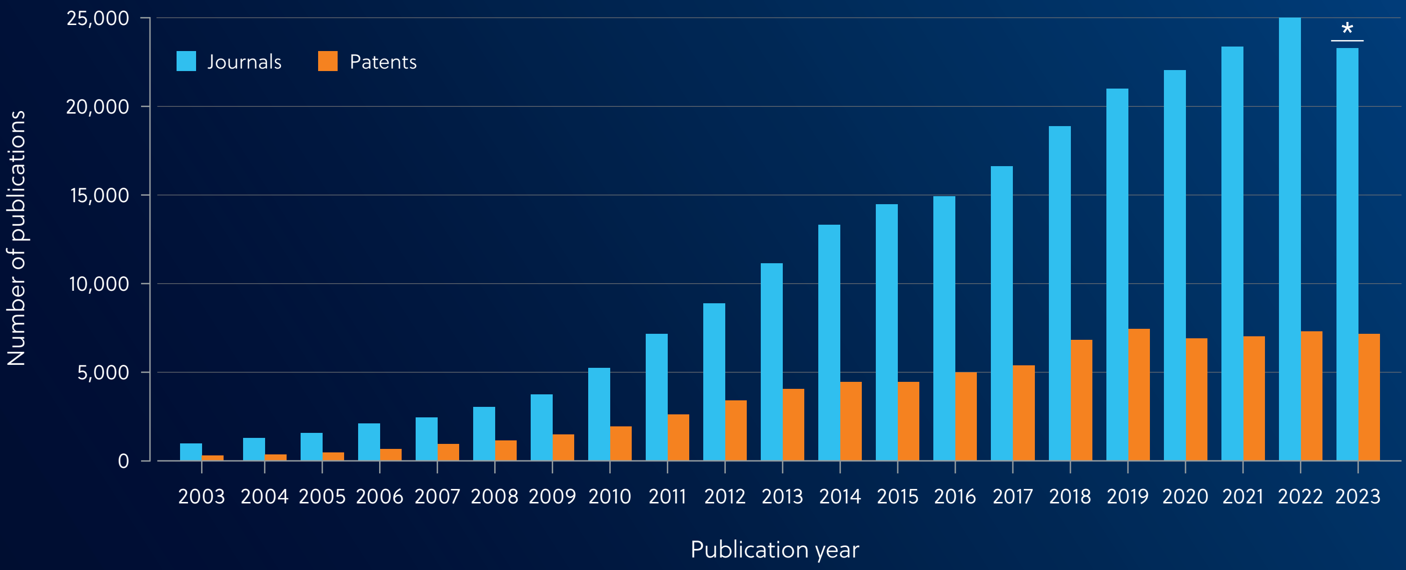

Figure 7. Publication trends for nanosensor-related research over the last two decades. Data includes journal and patent publications from the CAS Content Collection for the period 2003–2023.

The top 15 research organizations most actively involved in the field of nanosensors are mostly dominated by research organizations in the U.S. and China. The Chinese Academy of Sciences has nearly five times the number of journal publications compared to University of California, the most prolific research organization in the U.S.

The geographical distribution of the leading commercial patent assignees is more diverse, and includes eight countries: South Korea, the U.S., Japan, Germany, Finland, China, and the Netherlands. In contrast, the leading non-commercial patent assignees were composed overwhelmingly of organizations from China, with only two out of the top 15 leading assignees originating from South Korea.

A comprehensive analysis of substance data associated with nanosensors from our databases (CAS REGISTRY® and CAS Content Collection) reveals a steady increase in the number of individual substances used in nanosensor publications over the last two decades. This increase is more pronounced for journal publications than patent publications, with a ~25% increase between 2020 and 2022. Trends in nanosensor substances are discussed in more detail in the full papern the full ACS Nano Nanomaterials manuscript

Types of nanosensors

The publication distribution of sensor applications using nanostructures by stimuli and the rates of publication increase for various sensor types from 2018 to 2022. For most stimuli, the fraction of journal and patent publications are alike, implying similar proportions of exploratory and commercial interest. Chemical sensors form the largest fraction of publications, followed by biological sensors, physical sensors, and electromagnetic sensors (**Figure 8**).

Gas sensors make up the largest fraction of the different uses for nanosensors, with a similar prevalence of journal and patent publications. Surface plasma resonance (SPR)-based sensors and immunosensors make up the largest fractions of sensors for biological applications. While temperature sensors have received significant interest in patents, there is less interest in journal publications.

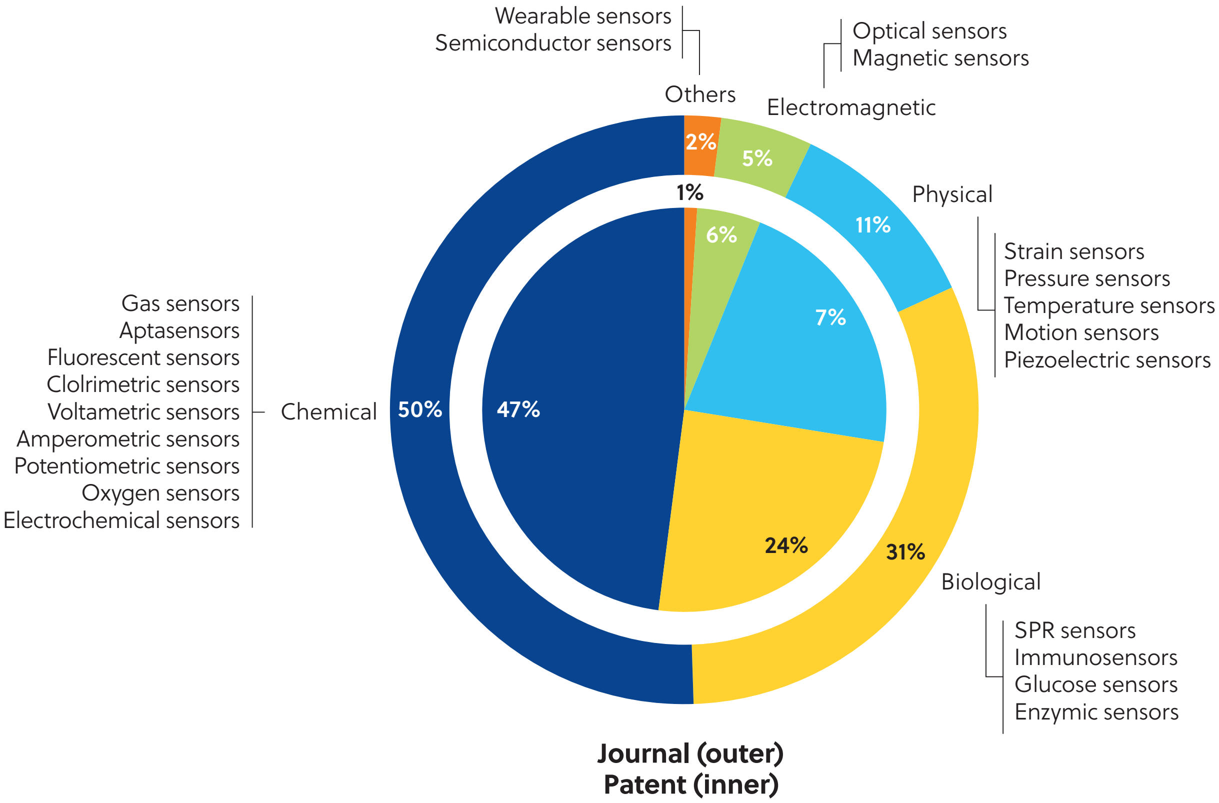

Figure 8. Publication distribution across broader categories of nanosensors. The outer donut chart represents journal publications while the inner pie chart represents patent publications. Data includes journal and patent publications from the CAS Content Collection between 2003–2023.

Applications of nanosensors

Nanosensor applications can be broadly categorized into the following industries: biomedical, environmental, agriculture, and food. Biomedical applications can be further broken down into cancer diagnosis and treatment, health monitoring using wearable sensors, pathogen detection, including bacterial species, and the detection of illicit drugs, including opioids, blood glucose detection, and biological imaging. Drug discovery is another major subset of biomedical applications and incorporates nanosensors in high-throughput screening to identify viable lead compounds. In our document dataset, biomedical nanosensor applications contribute to a larger extent of the overall publication count when compared with other applications (**Figure 9A**), accounting for nearly ~82% and ~80% of journal and patent publications, respectively. A few of these biomedical applications are discussed in further detail below:

Nanosensors in cancer: Nanosensors can be used to detect, monitor, and treat cancer. Due to their size and specificity, they can help detect specific biomarkers associated with cancer. For instance, a gold nanoparticle-based nanosensor array has been developed to detect volatile organic compounds from the exhaled breath of patients suffering from lung, breast, colorectal, and prostate cancers,[111] while nanosensors based on CNTs can also be used to detect cancer-related biomolecules in trace amounts.[112,113] Highly sensitive sensors using silicon or silver nanowires work by detecting subtle changes in electric conductivity upon their interaction with cancer biomarkers.[114,115]

Nanosensors in pathogen and infectious diseases detection: Nanosensors play a pivotal role in detecting pathogens, including bacteria, fungi, viruses, and protozoans, with high sensitivity and selectivity owing to their miniature size and ease of portability. Interactions between the functionalized nanomaterials and pathogenic species can induce changes in the sensor's physical, chemical, and electrical properties. These altered signals can then be measured and quantified for detection of the pathogen. Carbon-based nanosensors,[116] metallic nanoparticles,[117] and metal-oxide-based nanoparticles[118] are used for bacterial detection and therapy. Certain metallic nanoparticle-based nanosensors, such as silver and gold, experience localized changes in SPR.[119] Nanobiosensors are also being developed for fungi and viruses, particularly for the COVID-19 virus.[120,121]

Nanosensors in health monitoring: Nanosensors can efficiently detect specific biomolecules such as proteins, DNA, RNA, or metabolites and their altered levels by precisely monitoring biomolecular processes, including antibody and antigen interactions, enzyme interactions, and cellular communication activities. Subtle changes in the levels of these biomolecules could be indicative of health-related issues. Biosensors are also used to detect biological markers, perform continuous monitoring of biological parameters, and detect specific proteins and nanomechanical cell changes. Similarly, nanosensors can be used to perform pH monitoring in bodily fluids such as sweat or urinal fluids, which can aid in monitoring conditions such as acidosis and alkalosis and could indicate underlying health issues.[122,123] In addition, engineered nanoparticles can also help to develop imaging agents that bind to specific ligands to detect abnormalities at minute levels, which can aid in the early detection of disorders like cancer[124] and cardiovascular disease.[125]

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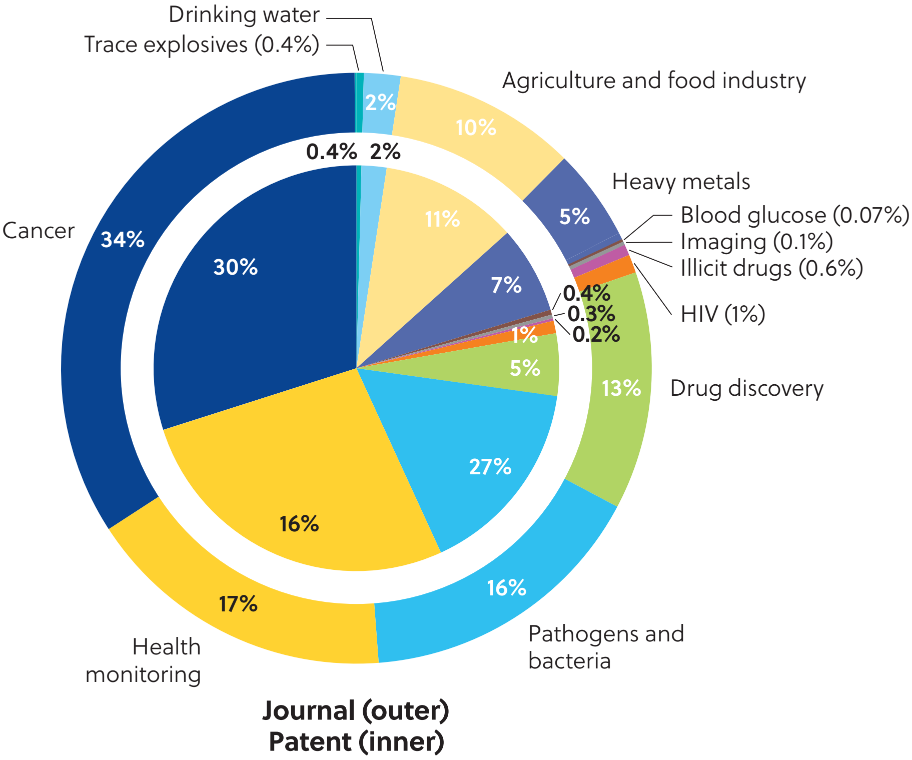

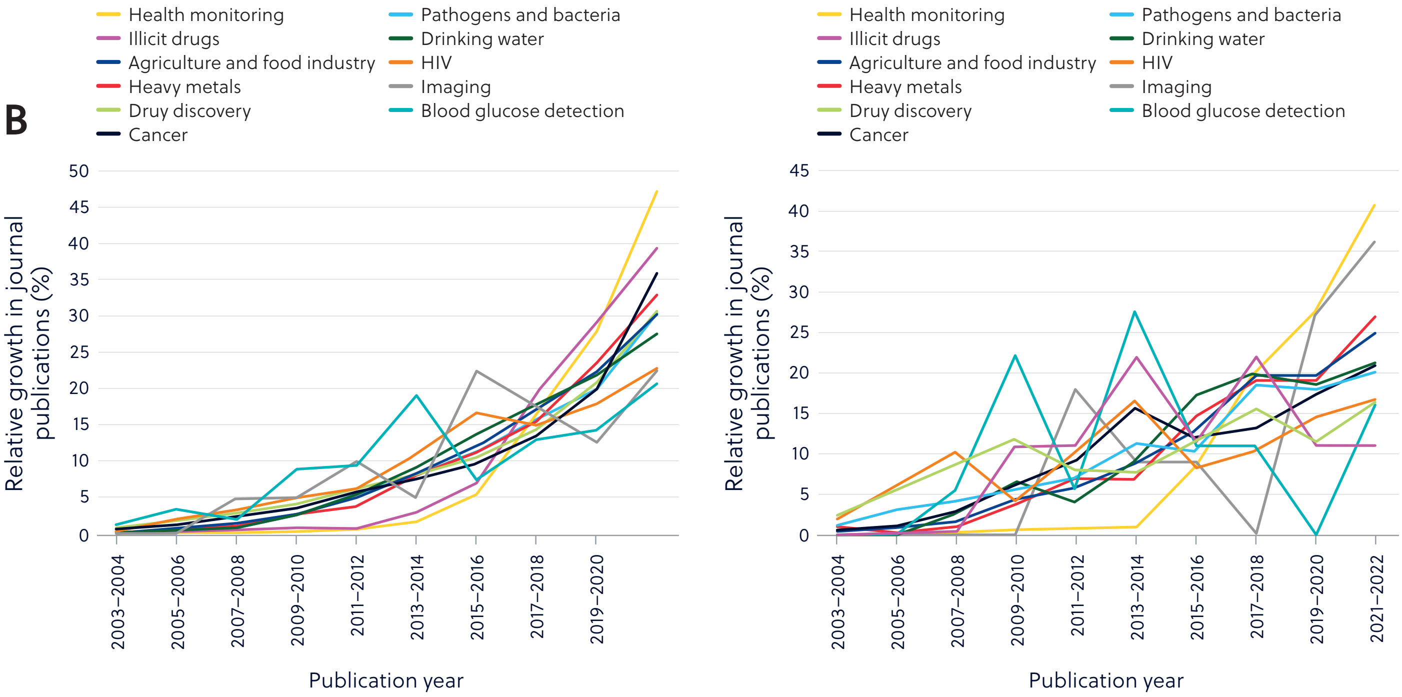

Figure 9. (A) Distribution of and (B) relative growth in publications (journals and patents) of various applications across which nanosensors appear to be utilized. Data includes journal and patent publications from the CAS Content Collection for the period 2003–2023.

Other key applications of nanosensors appear to be related to environmental monitoring and the agriculture and food industry; these applications account for a sizeable fraction of publications and show a steady increase in publications that is more pronounced after 2014. Environmental monitoring relates to detecting heavy metals[126–128] and monitoring water quality.[129,130] Agriculture and food-industry-related applications include the detection of contaminants (including pathogens) in food samples; RapidCheK™ is one commercially available nanosensor capable of rapidly detecting pathogens such as *Salmonella*, *E. coli* and *Listeria* in food samples.[131]

Summary

- Publications related to nanosensors have doubled over the last two decades, with notably slower growth in patent publications, indicative of a lag between research and commercialization.
- Biomedical applications of nanosensors account for ~80% of all journal and patent publications, most likely due to their utility in cancer diagnosis and treatment, health monitoring, pathogen detection, blood glucose, and biological imaging.
- Despite challenges associated with the application of nanosensors (including stability of nanomaterial-based sensors in harsh environments, miniaturization, and packaging, enhancing real-time monitoring capabilities, and balancing costs vs. materials), they have the potential to revolutionize various realms of science, including healthcare.

Nanosized drug delivery systems

Nanotechnology has revolutionized the biomedical and healthcare industry, with drug delivery systems (DDS) being one important application within the sector. Nanosized structures can stay in the blood circulation for a prolonged time, allowing for sustained release of the incorporated drug. Thus, nanosized DDS (nano-DDS) causes fewer plasma fluctuations than traditional DDS with reduced side effects.[132] Due to their size, nano-DDS can penetrate tissue, facilitate efficient drug delivery, and ensure activity at the targeted location. The uptake of nanostructures by cells is subsequently much higher than that of larger particles,[133,134] with nanostructures able to interact directly with the diseased cells to treat them. One significant achievement of medical nanotechnology is the modification/functionalization of nanoparticles to deliver drugs through the blood-brain barrier to target brain tumors.[135] Additionally, due to their size, shape and functionality, nanoparticle systems can form representative components of DNA delivery vectors,[136] which can penetrate deep into tissues with efficient absorption by cells.[137]

Publication trends

In recent years, sizeable methodological progress and a wealth of knowledge have promoted the advancement of research on nano-DDS, enhancing our understanding of their structure and efficiency. This is reflected in the consistent growth in related scientific publications (including journal articles and patents) over the last two decades (**Figure 10A**).

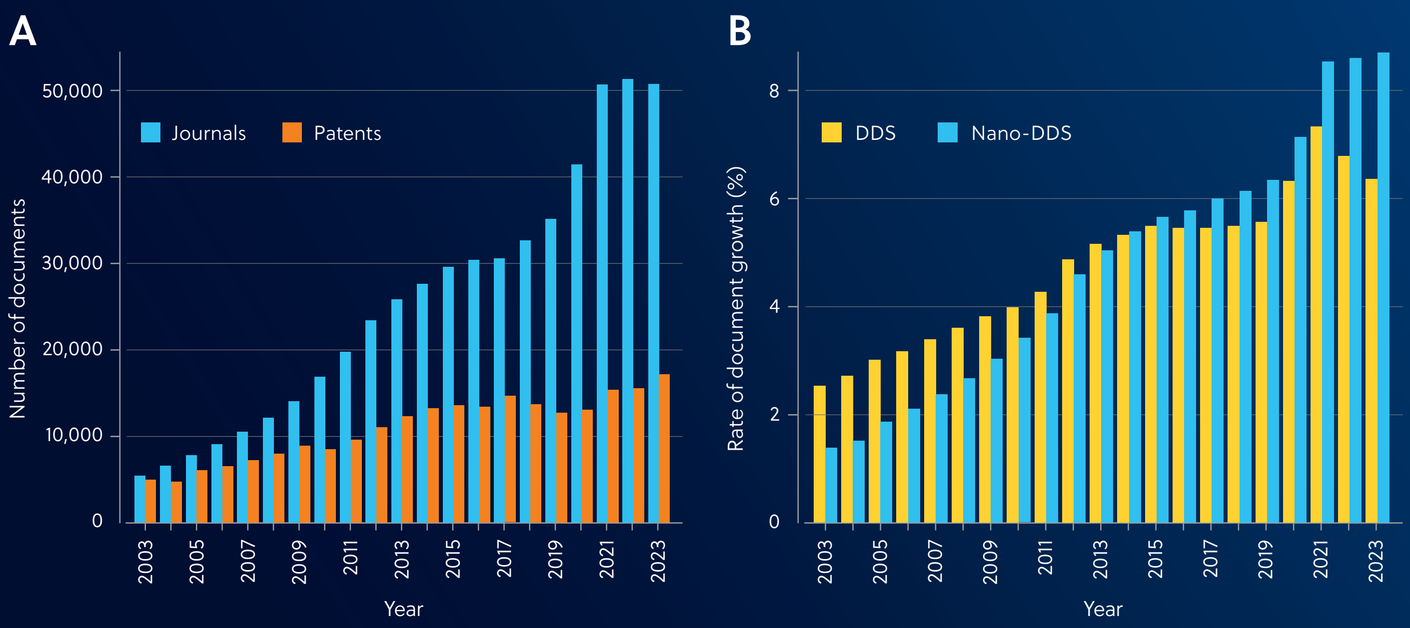

Figure 10. (A) Yearly growth of the number of documents (journal articles and patents) related to nano-DDS; (B) Yearly growth in nano-DDS vs. overall DDS-related documents. Data includes journal and patent publications from the CAS Content Collection from 2003–2023.

Journal article and patent publication counts related to nano-DDS have increased steadily over the past two decades, with journal articles increasing by over 30% in the last three years to approximately 50,000 publications in 2023 (Figure 10A). Patent growth has been slower, indicating the field is in the phase before the subsequent transition into patentable and more commercial applications.

China, the U.S., India, South Korea, and Japan are the leaders with respect to the number of published journal articles and patents related to nano-DDS research, with China and the Chinese Academy of Sciences dominating the field. Northwestern University, Stanford University, and the Massachusetts Institute of Technology, all from the U.S., have the highest number of citations per publication.

The University of California is the distinct leader in terms of the number of patents held by academic organizations. Among non-academic/commercial organizations, F. Hoffmann-La Roche (Switzerland), Procter & Gamble (U.S.), and Novartis (Switzerland) have the highest number of nano-DDS-related patents.

In **Figure 10B**, the yearly growth rate of publications in the CAS Content Collection related to nano-DDS is compared to those generally related to DDS. Between 2003–2013, nano-DDS-related publications demonstrated a slower growth rate vs. DDS-related publications as a whole. During the last decade, the number of publications related to nano-DDS has grown at a similar or greater rate, with a notable increase in the last three years. Recognizing the potential advantages of nano-DDS over traditional DDS has likely driven the increased interest in and publication rates of nano-DDS.

Key nano-DDS forms, materials, and applications

Continued interest resulting in extensive research and development has led to many nano-sized DDS forms. Analysis of more than 600,000 documents allowed the identification of these different nano-sized DDS forms, a few representative examples of which are discussed below.

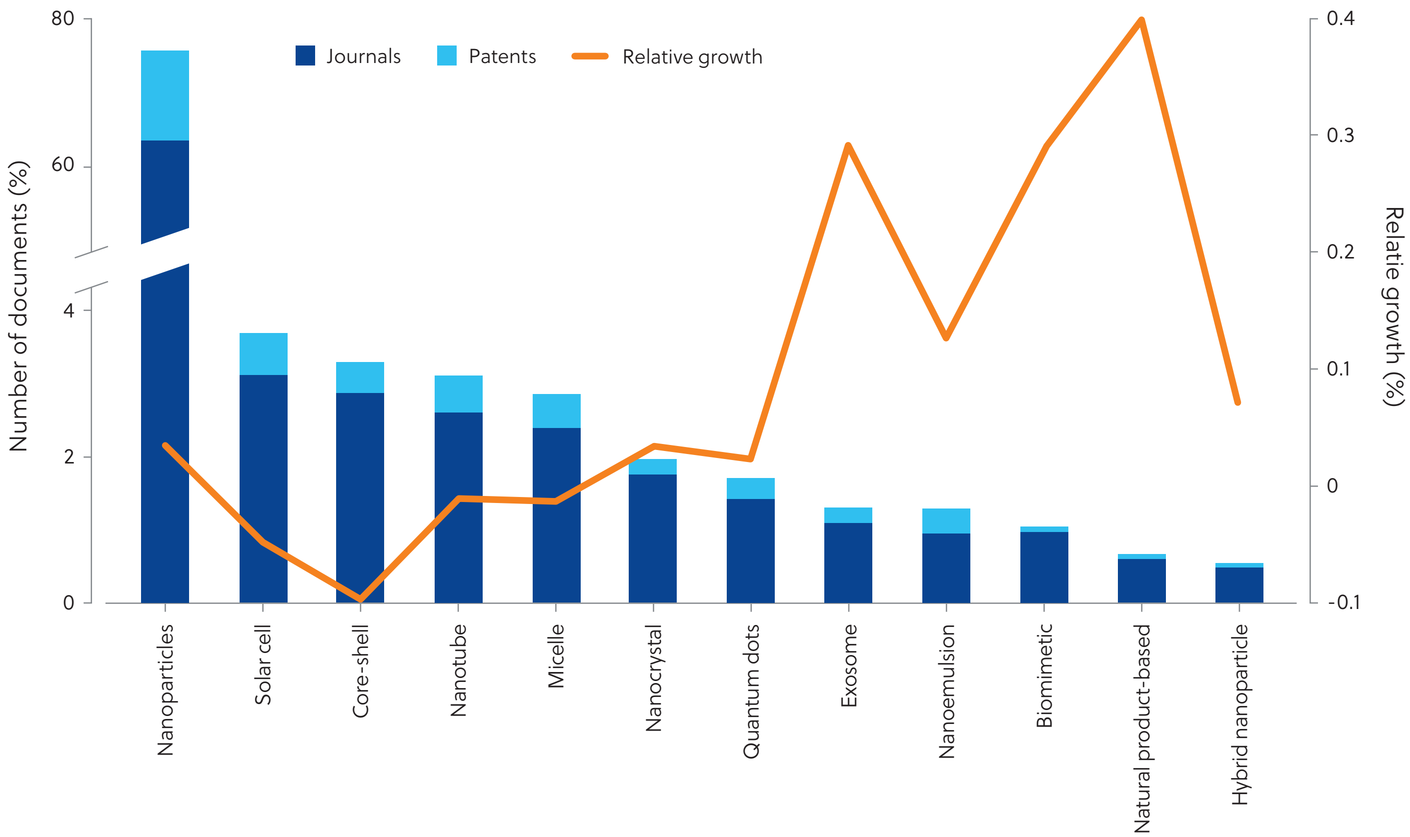

Figure 11. Percentage of documents (journal articles and patents, blue bars) and relative growth (orange line; calculated as the increase in the number of documents in the last three years normalized over the total number of documents for the given nano-DDS type) related to various nano-DDS types.

Nanoparticles are submicron-sized colloidal particles with tunable properties specifically designed for selective applications. The composition of the nanoparticle is chosen with respect to the target environment and/or anticipated effect. For example, biodegradable nanoparticles can be designed to degrade upon delivery, reducing their bioaccumulation and toxicity.[138] Metal nanoparticles have optical properties that allow for less invasive imaging techniques.[139] The photothermal response of nanoparticles to optical stimulation can also be exploited in tumor therapy.[140] Polymeric nanoparticles are currently the most popular class of nanoparticles in drug delivery, accounting for 32% of documents in the nano-DDS dataset in the CAS Content Collection. Lipid nanoparticles[141] are also widely used nanocarriers, contributing to 24% of publications in the nanoparticle DDS subset.

Natural product-based nano-DDS is the fastest-growing nano-DDS class in the CAS Content Collection (**Figure 11**). The combined use of nanotechnology, along with the variety of bioactive natural compounds, makes this an attractive prospect and has been growing in recent decades.[142] Nowadays, about 35% of pharmaceutical compounds are either from natural products or their derivatives and analogs, mainly including plants (25%), microorganisms (13%), and animal (3%) sources.[143] Natural compounds have been studied as a cure for disease owing to their valuable properties properties, such as inducing tumor-suppressing autophagy and antimicrobial activities. For example, autophagy has been exhibited by curcumin and caffeine[144] and antimicrobial effects have been shown by cinnamaldehyde, carvacrol, curcumin and eugenol.[145,146] The application of nanotechnologies leads to substantial enhancement of these properties, such as bioavailability, targeting, and controlled release. Thymoquinone, a bioactive compound in *Nigella sativa*, exhibited a six-fold increase in bioavailability after encapsulation in a lipid nanocarrier compared with free thymoquinone.[147] The pharmacokinetic characteristics of the encapsulated thymoquinone were also enhanced, optimizing its therapeutic effects.

Exosomes are valuable, natural nanocarriers for drug delivery due to their superior innate stability, low immunogenicity, biocompatibility, and excellent capacity for membrane penetration.[64] As important mediators of intercellular communications, exosomes are gaining interest in cancer immunotherapy.[148,149] Exosomes, which may be derived either from tumors (comprising tumor-associated antigens) or antigen-presenting dendritic cells, can trigger immune activation and, therefore, be used in developing anti-cancer vaccines.[150] Moreover, tumor-derived exosomes hold information from primary cells, meaning they can activate CD8 T-cells, offering a unique, alternative therapeutic approach for developing anti-cancer vaccines.[151,152]

Summary

- The application of nanotechnology in DDS is considered an emerging area of nanotechnology, which has the potential to overcome major limitations related to conventional DDS.
- This is reflected by steady growth in nano-DDS publications between 2003–2023, with comparable or faster growth rates for nano-DDS publications vs. DDS publications as a whole.
- The outlook for nano-DDS is promising, with ongoing research addressing challenges and paving the way for innovative and impactful therapeutic solutions.

Artificial intelligence (AI) in prominent nano-related fields

AI can play a significant role in nano-related research by helping researchers discover novel nanomaterials with desired features, predict their properties and applications of nanomaterials, and reduce the time it takes to analyze nanomachine output data.

Publication trends

Figure 12 shows the yearly distribution of publications related to the use of AI in nanoscience-associated research. Overall, the number of publications has steadily increased between 2003–2023. Journal publications dominate the field, with their total number being approximately seven times higher than patent publications. However, the overall patent-to-journal ratio has shown a steady increase in the last five years, indicating progression towards commercialization of research in this field.

Regarding geographical distribution, China dominates in the number of published journals, followed by Iran, India, and the U.S. China also leads the number of patent publications, with ~70% originating from China. The remaining ~30% of patent publications come from countries including India, the U.S., and South Korea, among others.

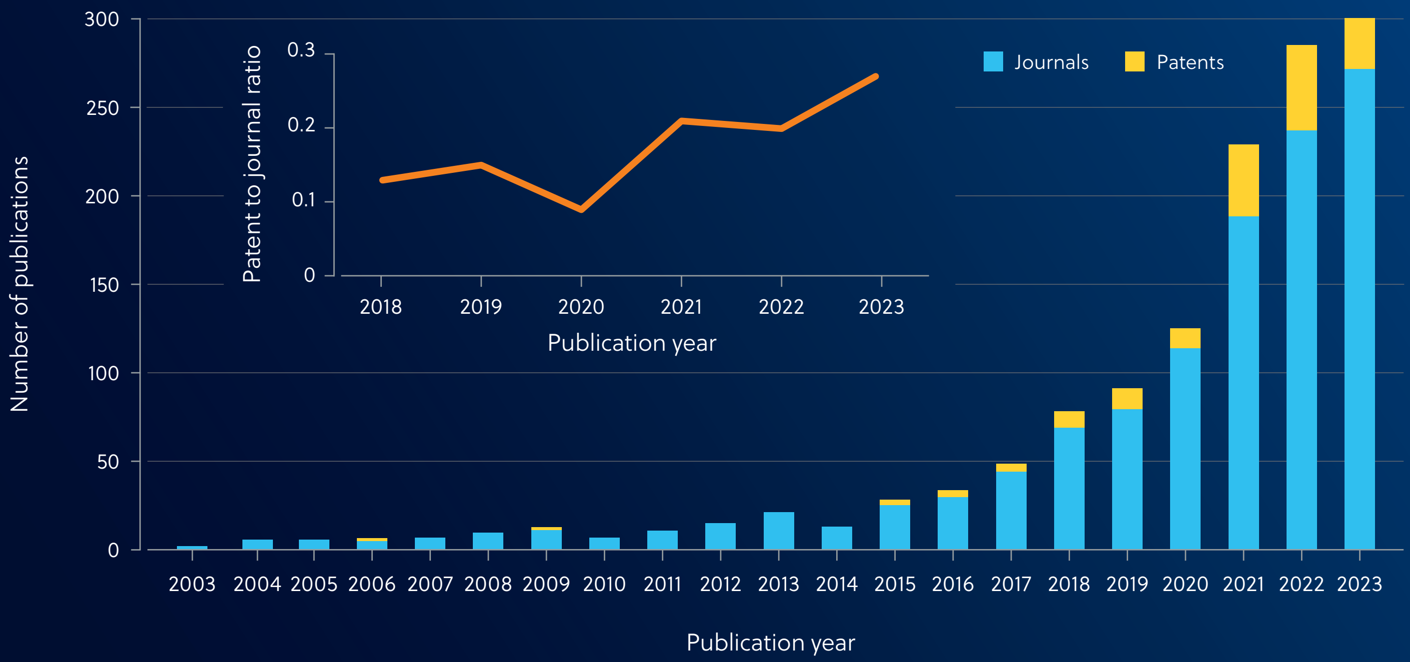

Figure 12. Number of journal and patent publications published per year from the CAS Content Collection that are related to the use of AI in nanoscience-related research areas (shown as blue and yellow bars, respectively) over the last two decades (2003–2022). The inset shows the trend for the patent-to-journal ratio for the last five years (2018–2023).

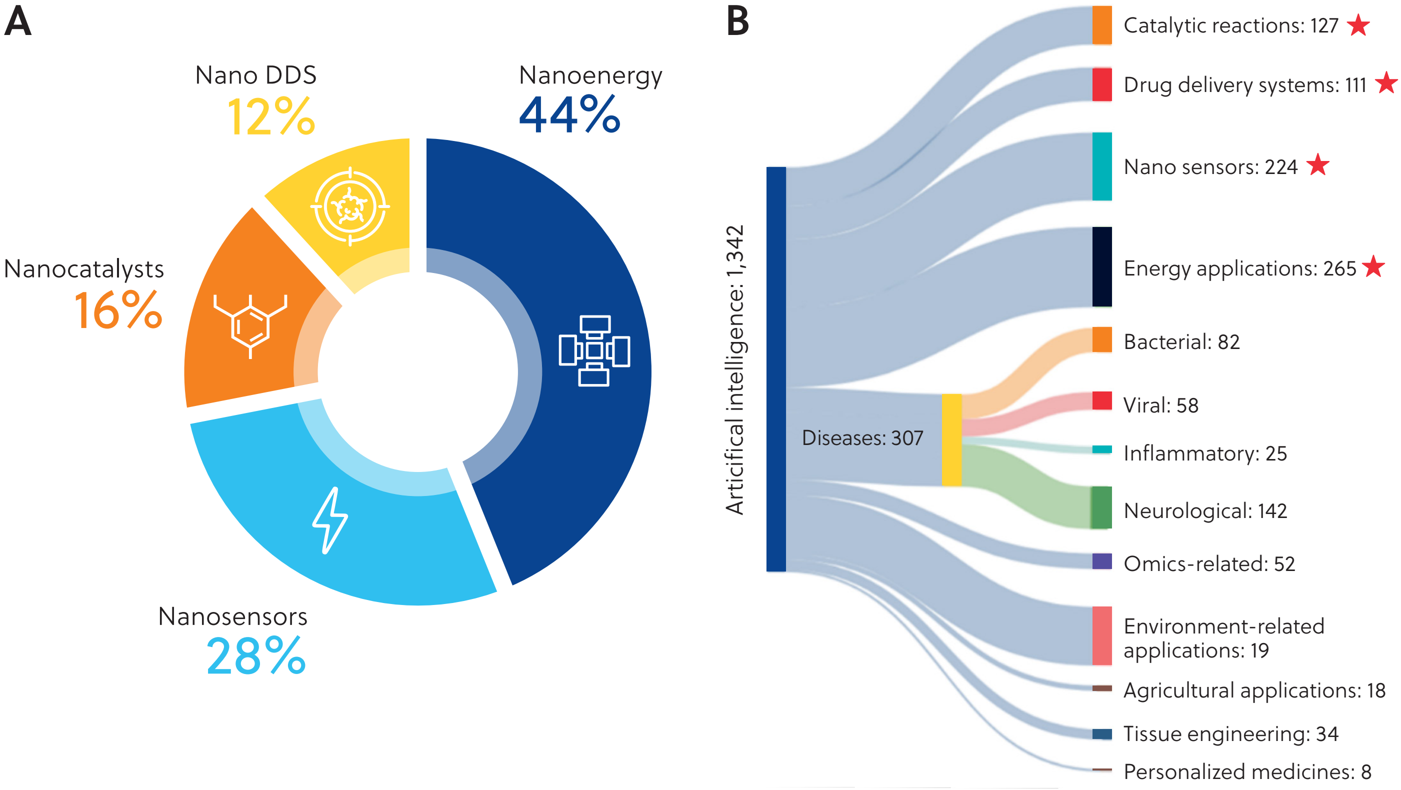

Figure 13. (A) Percentage distribution of AI use in prominent nano-related fields (Note: Nano DDS is used for nano drug delivery systems) (B) Sankey diagram showing correlations between uses of AI with applications in several nano-related fields derived from the CAS Content Collection.

The use of AI in the nano-related fields of energy and sensors is prominent, as demonstrated by the high percentage (44% and 28%, respectively) of scientific publications in these areas (**Figure 13A**). **Figure 13B** describes the use of AI in some of the nano-related fields discussed in this paper.

Applications

AI has revolutionized various scientific fields and advancements in computational approaches and nanomaterials have helped synergize these fields for various applications across diverse domains. For instance, advanced sensors such as image, vision, and wearable sensors use AI-based algorithms such as machine learning and neural networks to analyze the complex and multidimensional data output they generate.[153,154] AI-enabled nanosensors monitor data in real-time, improving the ability of healthcare providers to detect diseases, track onset and development, and continuously monitor health conditions.[155]

For nano-DDS, AI can help optimize various aspects such as drug design and formulation, controlled drug release, enhancing localized drug delivery, and target penetration.[156–158] The use of AI-enabled sensing technologies can also assist in designing nanoparticle-based personalized medicine and treatment optimization in the future with real-time monitoring and feedback capabilities.

Summary

- There has been a steady increase in the number of AI-related publications over the last two decades, accompanied by an increase in the overall patent-to-journal ratio.
- AI applications in nanomaterials are vast, with prominence in nanomaterials for energy applications and nanosensors.
- AI has the potential to accelerate nanoscience and nanomaterial development significantly.

Nanomaterials as catalysts

Nanoscience is most likely to improve the performance of heterogeneous catalysis because heterogeneous catalysis relies on structures larger than single molecules and depends on the structure, morphology, and size of the catalyst, features which nanoscience provides the opportunity to control.

Publication trends

Figure 14 shows the yearly publication trends in catalysis-related publications in nanoscience and demonstrates a steady increase in journal publications. In general, the number of patents per year also increased between 2003–2022, with the ratio of journals-to-patents (orange line in the figure) remaining between 3.5 and 5 during this period. Similar trends in patent and journal publications imply that a consistent fraction of academic research in this field can be commercialized.

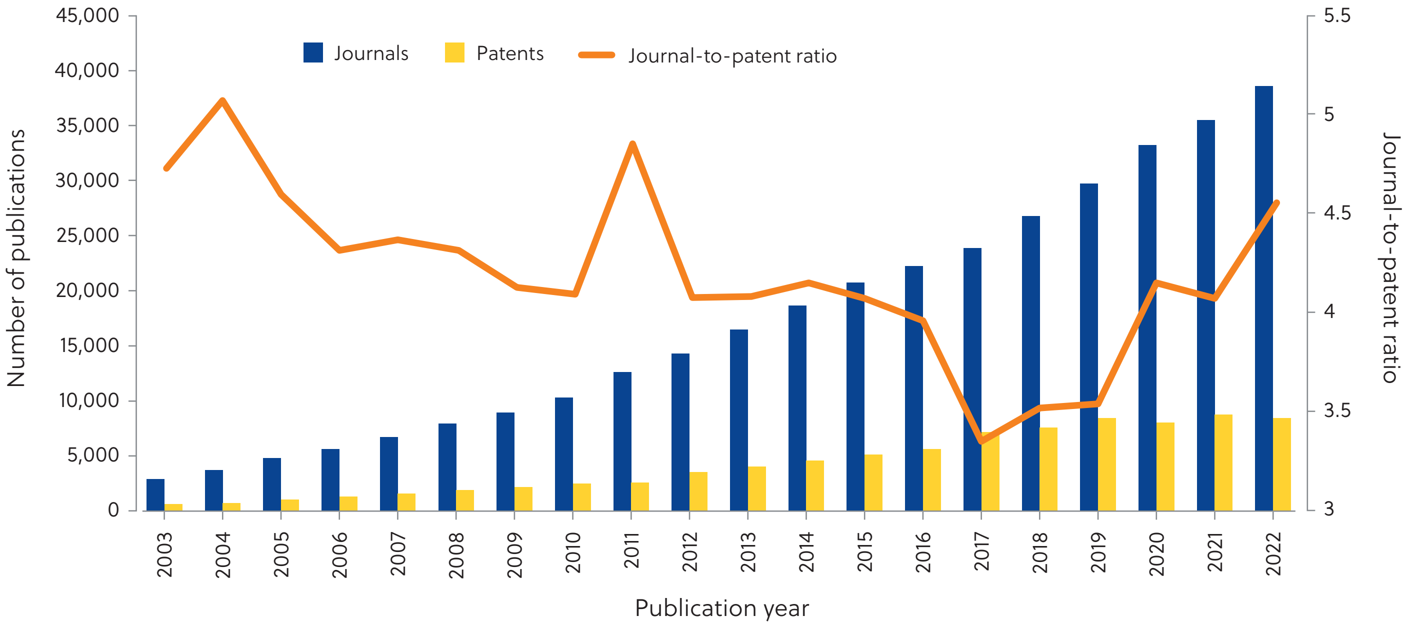

Figure 14. Number of catalysis-related publications in journals and patents from the CAS Content Collection between 2003–2022. The line shows the journal-to-patent ratio.

The Chinese Academy of Sciences published the highest number of journal articles related to catalytic nanomaterials followed by the Islamic Azad University of Iran. The remaining 20 universities are all in China.

China Petroleum and Chemicals Limited topped the list of commercial entities with patent applications, followed by Samsung Electronics and Toyota Motors. The top 20 non-commercial entities with patent applications are all academic institutions from China, showing the extent of interest in nanocatalyst research in this country.

Interestingly, the commercial entities belong to many industries including petroleum, automobiles, electronics, and chemicals, highlighting the wide-ranging applications of catalytic nanomaterials.

Substances used as catalysts

Metal oxides are the most used substance category in nanocatalysts, accounting for 34.9% of all substances used in catalysts, followed by noble metals (22.5%), transition metals (17.1%), and non-metals (15.1%):

- **Metal oxide nanomaterials** have applications in photocatalysis,[159] energy,[160] electrocatalysis,[161] and environmental remediation.[162]
- **Noble metals** have applications in electrocatalysis, photocatalysis, and organic synthesis.[163]
- **Transition metal catalysts** may be used in electrochemical CO_2 reduction,[164] hydrogenation,[165] and electrochemical water splitting.[166]
- **Carbon-based materials** such as carbon black are widely used as support for electrocatalysts,[167,168] whereas graphene has utilities as a catalyst in pollutant removal,[169] electrocatalytic nitrogen reduction,[170] and photocatalytic CO_2 reduction.[171]
- **Molybdenum disulfide and cadmium sulfide** are the most prominent metal sulfides employed in nanocatalysis, with cadmium sulfide used in photocatalysis[172] and molybdenum disulfide in sensors, bioimaging,[173] and electrocatalysis.[174]

Correlation between reactions and nanostructure types

CAS could also index the reaction types in the publications according to nanostructure type. This data is tabulated in **Figure 15** and the reaction types are arranged from left to right in the descending order of the number of documents in the nanocatalysts dataset. Changes in reaction preference with nanostructure likely indicate the preferences for reactions for specific catalyst nanostructures.

Overall, photocatalysis tops the list of reaction types, followed by electrochemical reactions. In all nanostructure types, photocatalysis reactions have the highest share. In the nanocomposites category, the top three reaction types are related to photocatalysis for water splitting and degradation of pollutants, followed by electrochemical reactions.

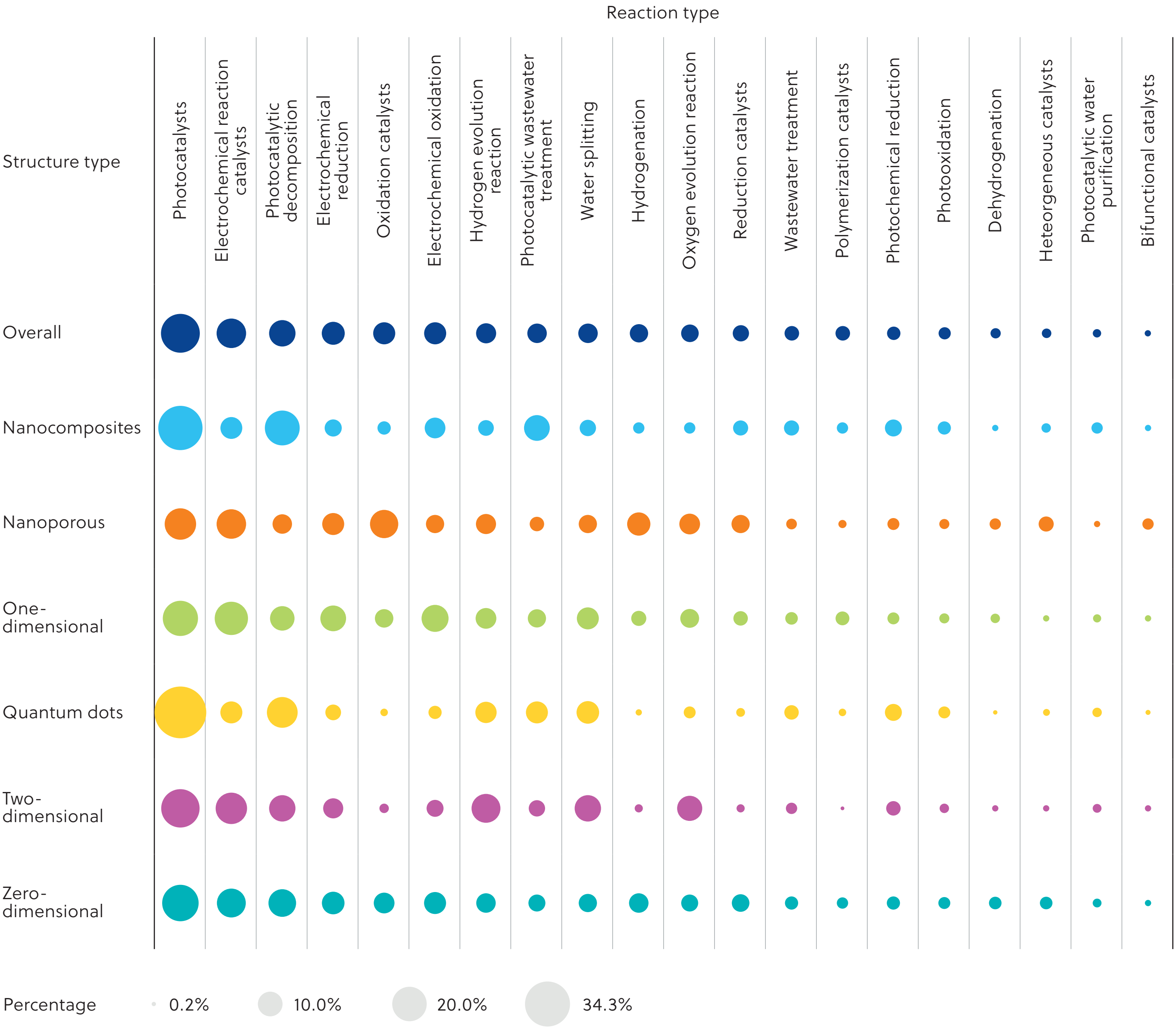

Figure 15. Percentage contribution of top reaction types within each nanostructure type and their comparison across the various nanostructure types. The percentages in this chart are calculated by considering the documents from these 20 selected reaction types as the total and does not include the numbers from the entire list of reaction types. The percentage contribution is visualized by the circle's size.

CAS also indexes the various apparatus reported in publications. The top apparatuses in the nanocatalyst dataset are related to electrodes, fuel cells, sensors, batteries, and photoelectrodes. For a detailed analysis of catalyst form vs. apparatus type, and information regarding the most studied catalyst properties, please refer to the full publication.[175]

Summary

- There have been similar increases in the number of journal and patent publications over the last two decades, implying a consistent fraction of the academic research in nanomaterials as catalysts lends itself to commercialization.
- Oxides tend to be the most used substance in nanocatalysts, while the top reaction types include photocatalytic, electrochemical, and heterogeneous catalytic reactions.

Conclusions

This insights report analyzed around three million documents related to the field of nanomaterials from the CAS Content Collection between 2003–2023. Analysis of these publications allowed us to gain insights into the emerging trends in this field and the most prominent applications. Unsurprisingly, some of the major uses of nanomaterials include their utility in energy-related applications and catalysis, as well as in drug-delivery systems and sensors. Their size and morphological, electrical, chemical, and thermal customizability explain why nanomaterials are such an attractive prospect across several sectors. However, there is still some disconnect between research and commercialization, as indicated by a lag between journal publication growth vs. patent publication growth. We foresee that interest will only continue to grow, with use expanding to different and new applications in the science, technology, and healthcare sectors.

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