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REVIEW

Functional particle nanoarchitectonics

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Abstract Nanoarchitectonics has emerged as a pivotal paradigm for the design and development of functional nanoparticles, enabling the precise integration of atoms, molecules, and nanoscale structures to create materials with novel properties and multifunctionality. This review highlights key advances in nanoparticle synthesis, structural control, and applications in catalysis, energy, environmental remediation, sensing, and biomedicine. Notable progress includes the creation of multifunctional core–shell particles, stimuli-responsive carriers, and high-performance biosensors, demonstrating enhanced performance and sustainability. By focusing on representative breakthroughs, we elucidate how nanoarchitectonics addresses challenges in energy efficiency, environmental safety, and advanced healthcare. The unique design philosophy of nanoarchitectonics underpins its role in achieving targeted delivery, high biocompatibility, and improved sensor capabilities, paving the way for next-generation materials and industrial applications. These recent developments illustrate the indispensable role of nanoarchitectonics in driving innovation for a sustainable and technologically advanced society.

Keywords Nanoarchitectonics · Nanoparticles · Energy · Environment · Catalysis · Biomedical applications

Introduction

Since its proposal in the early twenty-first century, nanoarchitectonics has developed over more than two decades [1] as a field characterized by an extensive and all-encompassing conceptual scope, making it challenging to describe comprehensively. In this review, we focus specifically on nanoparticles within this vast domain, providing an overview of recent progress by highlighting several representative topics.

The creation of functional materials through the control of nanostructures has advanced steadily in recent years by utilizing a range of methodologies.

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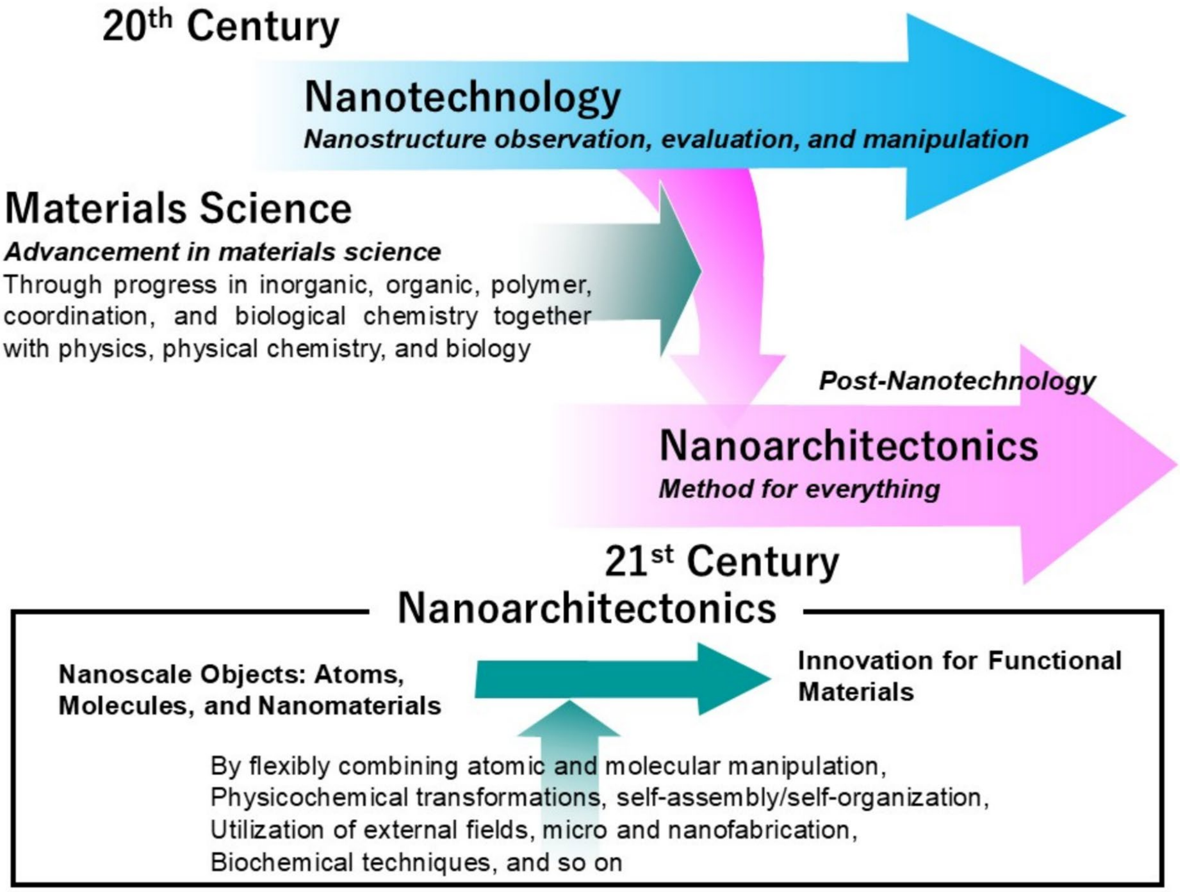
Nanoarchitectonics has emerged as a comprehensive concept that integrates these diverse approaches. Unlike conventional nanotechnology, which interprets nanoscale phenomena and manipulations in a unified context, nanoarchitectonics adopts a strategy of assembling fundamental units—such as atoms, molecules, and nanomaterials—to design and construct functional materials (Fig. 1) [2, 3]. Representing a “post-nanotechnology” paradigm [4], it pursues multidisciplinary integration across chemistry, physics, biology, and materials science. By flexibly combining atomic and molecular manipulation, physicochemical transformations, self-assembly/self-organization, utilization of external fields, macro and nanofabrication, and biochemical techniques according to specific objectives, nanoarchitectonics enables the creation of materials endowed with novel functionalities [5, 6].

Such an integrative approach to material design offers significant advantages over traditional methods based on single processes or equilibrium states, particularly in facilitating the formation of higher-order architectures such as asymmetric or hierarchical structures [7]. Conversely, interactions at the nanoscale are often accompanied by uncertainties arising from thermal fluctuations and quantum effects, making it unlikely for functions to emerge as a simple sum of individual components [8]. Instead, these systems tend to exhibit harmonious and collective behavior, resembling the coordinated operation of functional units in biological systems despite environmental noise or fluctuations. In this context, the ultimate objective of nanoarchitectonics can be seen as the creation of highly organized material systems that emulate the sophisticated functionality observed in living organisms [9].



Through progress in inorganic, organic, polymer, coordination, and biological chemistry together with physics, physical chemistry, and biology

By flexibly combining atomic and molecular manipulation,
Physicochemical transformations, self-assembly/self-organization,
Utilization of external fields, micro and nanofabrication,
Biochemical techniques, and so on

Fig. 1 Outline of the nanoarchitectonics concept

The principles and framework of nanoarchitectonics possess a remarkable universality, remaining largely independent of the specific materials, targeted functionalities, or fields of application. In recent years, there has been a noticeable rise in publications explicitly invoking nanoarchitectonics, with research described by this term encompassing a diverse range of topics. These include fundamental studies on material and structural control [10–14], investigations of physical phenomena [15–17] and biochemical mechanisms [18–20], and extend to practical advances in areas such as energy [21–24] (including solar cells [25–27], fuel cells [28–30], batteries [31–33], and supercapacitors [34–36]), environmental remediation [37–39], catalysis [40–43], various device [44–46] and sensor technologies [47–49], as well as drug delivery [50–52] and biomedical applications [53–55]. Given that all matter is composed of atoms and molecules, the potential scope of this approach is exceptionally broad. Just as the "theory of everything" represents the ultimate pursuit in physics [56], nanoarchitectonics in materials science may be regarded as a "method for everything" [57–59]. At the same time, it signifies a bold challenge to replicate, within a relatively short timeframe, the sophisticated functional systems that living organisms have developed over the course of natural evolution—an endeavor that may be considered a "final frontier" of the field.

Let us now consider the motivations behind the current demand for nanoarchitectonics, as well as the context in which it has emerged. Modern society faces a multitude of pressing challenges, the resolution of which is increasingly reliant on the advancement of sophisticated functional materials. Accelerated progress in materials development is observed across a broad spectrum of fields, including energy conversion and storage such as fuel cells [60–62], batteries [63–65], and supercapacitors [66–68], environmental remediation [69–71], promotion of carbon neutrality [72–74], utilization of biomass [75–77], drug delivery [78–80], biosensing [81–83], medical technologies [84–86], and information devices [87–89] and sensors [90–93]. Although efforts in these various domains may appear independent at first glance, they are fundamentally connected through a common trajectory rooted in the quest for highly functional material systems.

Human civilization initially progressed through the utilization of beneficial substances obtained from nature, gradually acquiring skills in processing and alloying these resources. However, with remarkable advancements in materials science during the twentieth century, humanity moved beyond reliance on natural materials, achieving the ability to generate novel substances through systematic scientific principles and technological innovations. This transformative trend continues today, as deeper insights into structures and phenomena, stemming from physics [94, 95], physical chemistry [96], and biology [97–99], are paralleled by ongoing progress in inorganic [100–102], organic [103–105], polymer [106–108], coordination [109–111], and biological chemistry [112–114], all of which remain central to technological innovation.

Furthermore, the process of materials development has revealed that the properties and functionalities of substances are determined not only by their intrinsic characteristics but also by the significance of their nanostructures [115–117]. Materials with identical compositions can exhibit markedly different behaviors depending on their size and internal architecture, with the control of nanostructures, in particular, unlocking a wide array of novel functionalities. Phenomena such as size effects at the nanoscale, enhanced catalytic activity resulting from increased surface area per unit volume [118, 119], and dramatic improvements in energy and charge transport efficiencies achieved through the organization of nanodomains [120, 121] all underscore the central role of nanostructure control in contemporary materials science. The full-scale emergence of this research area was made possible by nanotechnology, which has driven innovation in functional materials through the development of techniques for atomic- and molecular-level observation [122–124] and manipulation [125–127], as well as the analysis of nanoscale phenomena [128–130].

What is now sought at the forefront of this progress is the emergence of a new, comprehensive concept that unifies structure creation through materials chemistry with the precise control capabilities enabled by nanotechnology. This is embodied in nanoarchitectonics, heralded as a post-nanotechnology paradigm. Just as Richard Feynman's visionary ideas paved the way for nanotechnology in the mid-twentieth century [131, 132], nanoarchitectonics was articulated in the early twenty-first century by Aono et al. [133, 134]. This concept centers on the integrated assembly of fundamental components—atoms, molecules, and nanomaterials—to construct functional systems. While existing fields such as self-assembly in supramolecular chemistry [135–137], the development of metal–organic frameworks (MOFs) [138–140], covalent organic frameworks (COFs) [141–143], mesoporous materials [144–146], and interface science techniques (including self-assembled monolayers (SAMs) [147–149], Langmuir–Blodgett (LB) method [150–152], and layer-by-layer (LbL) assembly [153–155]) have each followed their own evolutionary pathways, nanoarchitectonics has begun to encompass and unify these topics, fostering interdisciplinary breakthroughs. Much like nanotechnology once consolidated a diverse set of pioneering research directions into a major movement, nanoarchitectonics is now taking on the integrative role required for the next generation of materials innovation.

As described above, nanoarchitectonics leverages structural control and organization at the nanoscale, integrating diverse technologies and expertise to impart entirely new functionalities to materials and devices. In the realm of nanoparticle development, this approach now enables advanced designs—such as hierarchical architectures, complex interfaces, core–shell and hollow morphologies—going beyond conventional control of composition, size, and shape [156–158]. These advancements hold the promise of significant performance improvements in diverse applications, including catalysis [159–161], sensing [162–164], energy devices [165–167], and biomedicine [168–170]. Moreover, precise arrangement and hierarchical assembly of particle ensembles [171–173], surface modification [174, 175], and the integration of heterogeneous materials [176, 177] have facilitated the realization of sophisticated properties such as molecular recognition and selective reactivity, while also making multifunctionality and synergistic effects more accessible. The introduction of self-organization and biomimetic strategies further enables the creation of sustainable and environmentally friendly materials, actively contributing to the realization of a more sustainable society.

Accordingly, nanoarchitectonics offers significant advantages across multiple facets, including enhanced structural design freedom, performance optimization, multifunctionality, and improved sustainability for a wide array of functional nanoparticles. As such, it has become an essential foundational technology underpinning cutting-edge materials development. In this review, we focus on several prototypical areas—synthesis and assembly, properties, applications in catalysis and energy, sensing and environmental fields, and biomedical uses—highlighting selected recent studies within each category to elucidate emerging trends. The intention is to discuss the unique contributions of nanoarchitectonics to the development of functional nanoparticles, rather than to provide a comprehensive overview of all state-of-the-art research in each domain. Based on the selected examples and their analysis, general tendencies are outlined. Finally, we discuss prospective directions required for future advances in nanoarchitectonics-driven nanoparticle research.

Synthesis and assembly

The concept of nanoarchitectonics has become increasingly important in both the fabrication of materials and the formation of their assemblies. Nanoarchitectonics involves the deliberate integration of atoms, molecules, and nanostructures to engineer materials with innovative properties and functionalities. These processes cover an extensive variety of sophisticated techniques, ranging from the precise manipulation and control of atoms and molecules to the physical alteration and reshaping of materials at different scales and the chemical conversion and transformation of substances through various reactions, including organic synthesis. Furthermore, the spectrum of processes also involves self-assembly and self-organization, whereby materials spontaneously arrange themselves based on inherent properties, as well as the use of external fields and forces to guide and control the orientation, structure, and arrangement of materials. Techniques such as nanofabrication and microfabrication, which enable the creation of intricate structures at the nanoscale and microscale, are also encompassed, along with biochemical processes that involve the use of biological molecules and systems for material construction. In the realm of nanoarchitectonics, the construction of functional materials requires not only the careful and strategic selection of these diverse processes but also their effective integration and combination, allowing for the development of materials with advanced functionalities and tailored properties for specific applications.

In this section, we focus on the creation of substances, highlighting diverse applications and the emerging value of nanoarchitectonics through recent cutting-edge research examples. By comparing various studies, we provide an overview of how structural design at the nanoscale contributes to the maximization of material performance and the development of entirely new functionalities.

Xian et al. prepared ultrafine platinum nanoparticles (Pt/Co-N-C) by irradiating a mixture of Co-N-C and $K_2[PtCl_4]$ with near-ultraviolet light at 395 nm as well as visible light at 450 nm and 550 nm, without the addition of any reducing or stabilizing agents, employing a MOF-modified carbon material (Co-N-C) as the support (Fig. 2) [178]. The Pt nanoparticles were uniformly dispersed on the Co-N-C surface, with particle sizes ranging from 2.39 to 3.53 nm. In the reduction of 4-nitrophenol, the catalyst synthesized under 395 nm near-UV light (Pt/Co-N-C-1) exhibited the highest catalytic activity, maintaining approximately 90% conversion even after five cycles, thereby demonstrating good recyclability. The use of 395 nm light favored adjustment of the platinum species distribution during the reaction, promoted the formation of smaller platinum nanocrystals, and contributed to the generation of highly active catalysts. This methodology suggests potential for green synthesis routes as well as the preparation of single-atom and subnanocluster catalysts. The use of MOF-modified carbon supports and precise photochemical synthesis of ultrafine Pt nanoparticles in this study exemplifies a nanoarchitectonics approach, wherein functional materials are constructed from the nanoscale upwards. Nanoarchitectonics enables the precise design of structures at the atomic and molecular levels, offering control over nanoparticle dispersion, size, and surface characteristics, thereby realizing high-performance materials. From this perspective, the technique described in this paper embodies key principles of nanoarchitectonics, including solvent-free and stabilizer-free green processing, controlled nanoparticle sizing, and synergistic effects with the support. As a result, the method facilitates the design of highly active and durable catalysts, enables applications in single-atom and subnanocluster systems, and contributes to the advancement of environmentally friendly synthesis and novel functional materials.

The development of high-entropy materials has attracted significant attention due to their exceptional properties and numerous advantages. Nevertheless, achieving nanoscale morphological control in these multielement systems presents substantial challenges owing to their structural complexity. Yagi et al. successfully synthesized compositionally diverse mesoporous high-entropy materials, containing elements up to Ir, through a wet-chemical reduction method combined with selenium incorporation [179].

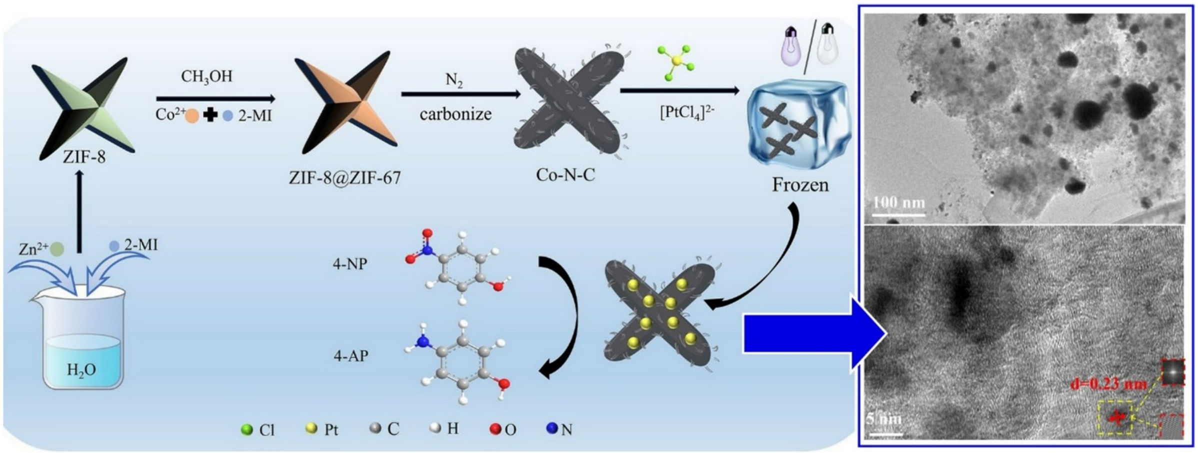


Fig. 2 Synthetic scheme for ultrafine platinum nanoparticles (Pt/Co-N-C) by irradiating a mixture of Co-N-C and $K_2[PtCl_4]$, employing a MOF-modified carbon material (Co-N-C) as the support and TEM images. Reprinted with permission from Ref. 178 Copyright 2025 Oxford University Press

The introduction of polymer micelles facilitated the formation of uniform porous structures, while tuning the selenium content allowed for precise control over Ir incorporation and the overall mixing entropy. During the reduction process, metallic and selenium ions were reduced and aggregated, with the polymer micelles guiding the development of mesoscale porosity. It was observed that Ir content within the high-entropy materials increased in tandem with selenium proportion, resulting in higher mixing entropy. This approach yielded homogeneous elemental distribution and consistent mesoporous structures, suggesting promising new pathways for applications such as catalysis. The design of nanoscale porosity using polymer micelles and the multielemental control enabled by selenium incorporation represent quintessential examples of precise structural tuning and functional realization through nanoarchitectonics. This strategy enables the integration of features such as porosity, compositional uniformity, and high entropy at the nanoscale, leading to the emergence of advanced functionalities—such as novel catalytic properties—not achievable with conventional materials. Nanoarchitectonics, therefore, plays a pivotal role in uniting practicality and innovation within materials science.

Tajikawa et al. demonstrated that the selective addition of small amounts of isobutyl- or phenyl-substituted four-leaf clover-shaped cage silsesquioxane derivatives to poly(methyl methacrylate) enables either surface segregation or enhancement of bulk properties [180]. The C_3- and C_4-linked isobutyl- and phenyl-substituted four-leaf clover-shaped cage silsesquioxane derivatives were synthesized by hydrosilylation of the corresponding monoallyl- and monohexenyl-polyhedral oligomeric silsesquioxane (POSS), double-decker silsesquioxane, and poly(methyl methacrylate). Isobutyl-substituted POSS exhibited surface segregation in poly(methyl methacrylate) films, resulting in high water contact angles and maintained optical transparency. In contrast, phenyl-substituted POSS remained dispersed within the polymer matrix, increasing the glass transition temperature (Tg) of the polymer but rendering the film semitransparent. Further research is needed to optimize surface segregation and bulk property improvements, including the impact of processing conditions. This study provides a concrete illustration of the nanoarchitectonics concept, wherein structure is designed at the nanoscale to create novel functional materials. The choice of substituents and linkage modes in the POSS molecules has a direct impact on surface segregation behavior and bulk characteristics. Molecular arrangement and aggregation states at the nanometric level produce significant changes in film properties. Precise molecular design and assembly control through nanoarchitectonics enhance surface characteristics and physical properties of resin materials, facilitating the development of optimized functional materials for various applications.

In their paper titled “Membrane Nanoarchitectonics with Non-Ionic Surfactants and Nanoparticles,” Costa et al. investigated the behavior of bilayer systems formed by doping a nonionic surfactant (Simulsol M45) and 1% Laponite solution [181]. Structural analysis of these nanosystems using small-angle X-ray scattering (SAXS) revealed that when the lamellar spacing exceeds the thickness of the nanoparticles, Laponite nanodisks can be incorporated into the bilayer, and lamellar phases are present across the entire range of surfactant concentrations. Structure factor and electron density data further demonstrated that the incorporation of Laponite nanoparticles into the lipid bilayers significantly affects the system’s structural properties, with both bilayer thickness and lamellar periodicity modulated by surfactant concentration. This system shows promise for practical applications such as water purification and drug delivery, and future work will focus on detailed investigations of particle organization under varying conditions such as temperature and additives. This research exemplifies the nanoarchitectonics approach by employing precise structural control over composites built from Laponite nanoparticles and surfactants. The insertion of nanoparticles into bilayers and the tunability of lamellar periodicity and thickness at the nanoscale result in emergent functional properties, paving the way for advanced applications in drug delivery and water treatment. The nanoarchitectonics concept enables the self-organization of nanomaterials and the realization of their functionalities, while the optimization of processing conditions further contributes to the creation of sustainable, high-performance materials.

As illustrated by the above examples, nanoarchitectonics is an innovative concept that enables the rational creation of novel functional materials through the precise design and arrangement of atoms, molecules, and nanoparticles. For instance, the utilization of MOF-modified carbon (Co-N-C) allowed for the uniform and ultrafine dispersion of platinum nanoparticles via simple light irradiation, achieving green synthesis without the need for reducing or stabilizing agents. The integration of wet-chemical techniques with selenium incorporation and polymer micelles facilitated the nanoscale formation of high-entropy, multielement, and mesoporous structures, laying the groundwork for next-generation functional materials such as advanced catalysts. Through molecular design, selective control over surface segregation and bulk properties of POSS derivatives was accomplished, enabling optimization of material functionalities. SAXS analysis was employed to precisely control composite structures comprising nanoparticles and surfactants, resulting in the development of bilayer functional materials. These cases demonstrate that nanoarchitectonics makes possible the sophisticated integration of structural design, material performance, and environmentally conscious synthesis, thereby assuming a vital role in the development of next-generation high-performance materials and the realization of a sustainable society.

Properties

Advancement in materials science based on nanoarchitectonics fundamentally relies on detailed characterization and analysis of material properties. This is especially critical for materials at the atomic and molecular level, such as nanoparticles and nanoclusters, whose properties can change drastically in response to minor structural modifications and environmental influences. Consequently, property analysis not only elucidates the mechanisms by which materials exhibit specific functionalities but also serves as a crucial foundation for the design and application of novel, high-performance materials. In this section, we provide an overview of state-of-the-art property characterization techniques for nanoparticle assemblies and metal nanoclusters, highlighting their significance and value.

The properties and underlying principles of self-organized nanoparticle assemblies have attracted considerable interest. For example, Zbonikowski et al., in their paper titled "Langmuir Nanoarchitectonics of Thermoresponsive Adaptive System of PNIPAM-Decorated Nanoparticles," revealed that the self-organization of poly(N-isopropylacrylamide)-coated iron oxide–silica nanoparticles at the air–water interface can be significantly modulated by ionic strength (Fig. 3) [182]. Upon the addition of KCl, the interparticle distance increased, indicating that effects arising from ionic clouds and osmotic pressure—distinct from conventional electrostatic screening—governed the aggregation and membrane formation of the particles. Their observations showed that the potential of interparticle interactions shifted to longer distances, with short-range repulsion being active at much larger separations compared to pure water. At the same time, the minimum of the long-range attractive potential became deeper than that in water, and "drifting ice-like" aggregates were visualized by Brewster angle microscopy. According to the Derjaguin–Landau–Verwey–Overbeek (DLVO) theory, the introduction of ions should shorten interaction distances through electrostatic screening; however, the experiments revealed the opposite trend. The

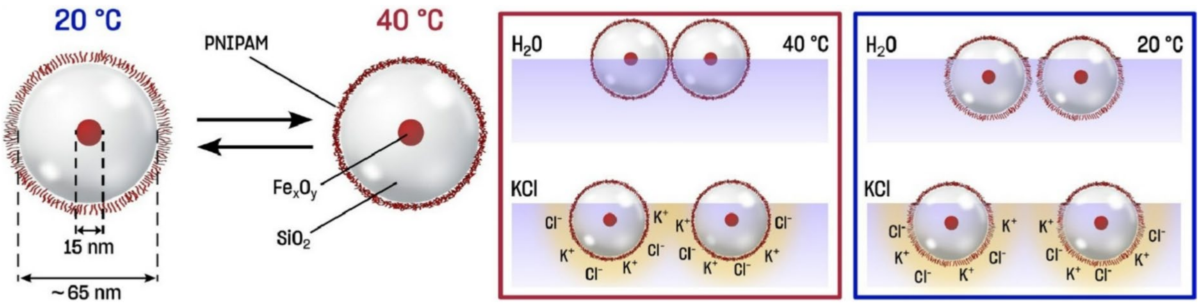


Fig. 3 Self-organization of poly(N-isopropylacrylamide)-coated iron oxide–silica nanoparticles at the air–water interface modulated by ionic strength and temperature. Reproduced under terms of the CC-BY license from Ref. 182, 2025 American Chemical Society

authors propose that locally concentrated excess ions induce water influx, thereby increasing osmotic pressure and generating long-range repulsive forces. For PSiFe nanoparticles at the KCl solution surface, the accumulation of excess ions at the interface led to an imbalance in ion distribution between surface and bulk, ultimately expanding the interparticle distance via osmotic effects. This striking phenomenon suggests new opportunities for designing stimuli-responsive materials and smart surfaces, presenting a novel strategy for controlling the organization of nanoparticle assemblies. This work exemplifies the nanoarchitectonics approach, where interfacial organization and interactions of nanoparticles are actively manipulated through environmental parameters such as ionic strength and temperature. The design of nanoparticle coatings and ionic environments enables precise adjustment of interparticle distances and aggregation states, embodying the essential value of nanoarchitectonics: the construction of nanoscale architectures for tailored function. As a result, these principles can be applied to the development of environmentally adaptive, high-performance materials and smart coatings, underlining the importance of bottom-up nanoscale design in advanced materials science.

Metal nanoclusters possess atomically precise structures and quantum-confined electronic states, exhibiting unique photophysical properties that arise from electronic transitions between discrete energy levels. While their structural behavior in the ground state has been widely investigated, many aspects of their excited-state dynamics remain elusive. These dynamics include relaxation pathways, structural transformations, and the spatial distribution of excitons. In a recent review, Ishii and Nakashima comprehensively demonstrated that the excited-state dynamics of metal nanoclusters are highly sensitive to factors such as composition, surface structure, solvent, and the surrounding ionic environment [183]. Notably, they showcased how the dynamic interactions of counter ions in the excited state can modulate energy levels, spatial localization, and chiroptical activity. Even minimal changes in structure or environment can alter key excited-state relaxation processes—including intersystem crossing, internal conversion, and photoluminescence—enabling fine-tuning of excitation energy, lifetimes, spatial localization, and coupling with vibrational modes. Recent findings highlight that dynamic interactions between the nanocluster core and counter ions can efficiently regulate the energy and distribution of excited states, not only via static modifications of composition or structure but also through dynamic processes occurring within the excited-state lifetime. Leveraging the ionic nature of nanoclusters and the long-lived triplet states, it is possible to design the energy and localization of excited states to respond to external ionic stimuli. Such dynamic strategies introduce a new paradigm for the design of photophysical and chiroptical functionalities in nanocluster materials. This knowledge expands the design toolbox for advanced optofunctional nanocluster materials, demonstrating that both static structural tuning and dynamic environmental modulation are effective for advanced functionality. The insights provided in this review exemplify how nanoarchitectonics enables atomic- and ionic-level manipulation of structure and environment, facilitating precise control over the excited-state properties and functionalities of metal nanoclusters. The design of photophysical properties and chiral activity through dynamic ion interactions and subtle structural adjustments is directly aligned with the nanoarchitectonics philosophy of creating function from the molecular and nanoscale. Incorporating dynamic responsiveness into material design is anticipated to drive the future development of sophisticated, multifunctional, light-responsive nanomaterials in materials science.

Geometry and topology endow mechanical frames with remarkable properties, from shape morphing to phonon manipulation, that can drive innovative technologies. However, while significant progress has been made in the study of macroscopic frames, realizing mechanical metamaterials and phonon imaging at the nanoscale has remained challenging. Qian et al. extended topological mechanical frame principles to self-assembled nanoparticle lattices and, using liquid-phase transmission electron microscopy (TEM), elucidated the phonon dynamics at this scale (Fig. 4) [184]. In this work, the principles of topology-designed mechanical frames were applied to nanoparticle self-assembled lattices, enabling direct measurement of phonon band structures, nanoscale spring constants, and lattice deformation pathways via liquid-phase TEM. Maxwell lattices, characterized by perfect hinges that constrain longitudinal motion while preserving rotational freedom, were achieved using anisotropic gold nanocubes. The study revealed

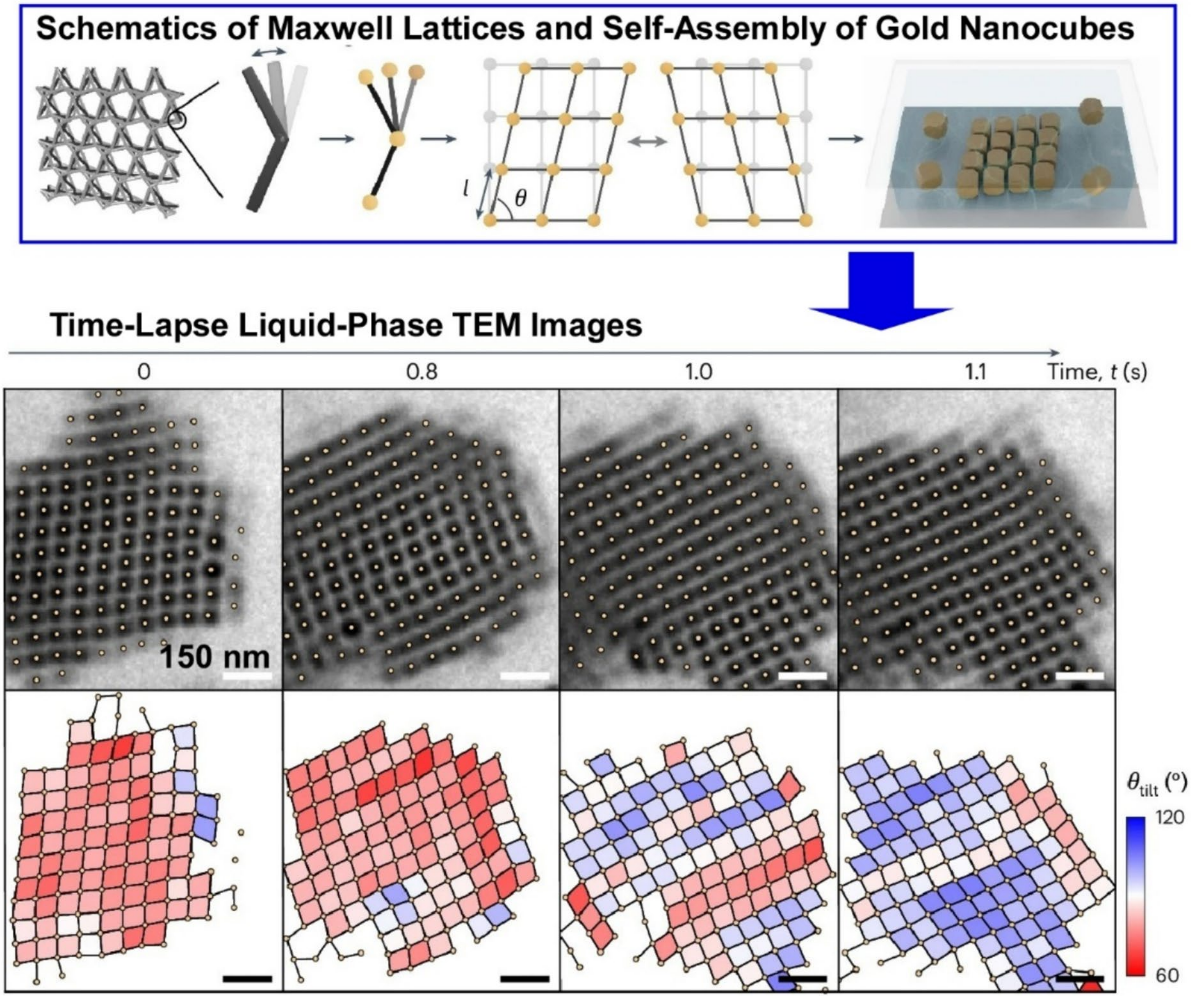


Fig. 4 Topological mechanical frame principles to self-assembled nanoparticle lattices: Maxwell lattices, characterized by perfect hinges that constrain longitudinal motion while preserving rotational freedom, filled with gold nanocubes (top) and time-lapse images using liquid-phase transmission electron microscopy (bottom). Reprinted with permission from Ref. 184 Copyright 2025 Springer-Nature

control over phonon modes and lattice reconstruction within Maxwell lattices and underscored the crucial roles of many-body and non-nearest-neighbor interactions. By engineering nanoparticle shape, size, organization, and interactions, the phononic properties can be finely tuned, opening avenues for next-generation functional materials in areas such as acoustic wave manipulation, imaging, and memory storage. This review embodies the concept of nanoarchitectonics—realizing structural design through nanoparticle self-assembly paired with nanoscale control of mechanical properties and phonon behavior. Precise manipulation of lattice geometry and interactions at the particle level, including topology and many-body effects, enables the creation of new functionalities. Nanoarchitectonics-driven structural engineering thus offers a versatile platform for designing acoustic, mechanical, and information-processing materials, making significant contributions to unexplored directions in nanoscale functional materials.

As illustrated by the above examples, the significance of nanoarchitectonics and property analysis is becoming increasingly pronounced. In structures formed by the self-assembly of nanoparticles, interparticle interactions and interfacial phenomena play a decisive role in determining material properties and serve as a foundation for new material design. For instance, interface control in self-assembled nanoparticle systems enables fine-tuning of interparticle distances and aggregation states through the design of ionic environments and surface coatings, directly enabling advances in stimuli-responsive materials and smart surfaces. Furthermore, in metal nanoclusters, recent reports demonstrate that, beyond static structural modification, sophisticated control of excited-state dynamics and photophysical properties can be achieved through dynamic environmental responses and ion interactions—making molecular- and ionic-level property analysis indispensable for function-driven design. The application of geometric and topological design to nanoparticle lattices also allows precise control over phonon modes and lattice deformation pathways, paving the way for next-generation mechanical and acoustic materials. Collectively, these cases make it evident that the integration of precise structural design and advanced property analysis based on nanoarchitectonics is key to creating functional materials and enabling novel technological developments.

Catalyst to energy

In modern society, catalytic functionalities are central to enhancing the efficiency of chemical reactions and underpinning energy conversion technologies, whose importance continues to grow. Achieving a sustainable society requires highly efficient and environmentally friendly energy conversion and resource-circulating chemical processes—both of which depend fundamentally on functional catalysts. Improvements in catalytic performance, stability, and selectivity are directly linked to technological breakthroughs across a wide spectrum of energy applications, including biomass conversion, carbon dioxide reduction, and hydrogen production. This section introduces the latest advances in catalyst design and energy-related applications enabled by nanoarchitectonics-based approaches.

Low-polymerized Zr–O–Zr units within hydrated zirconia (ZrO_2(H)) exhibit exceptionally high activity for the catalytic transfer hydrogenation of furfural to furfuryl alcohol. However, during the catalytic reaction, dehydration among Zr–OH groups leads to the formation of more highly polymerized structures, resulting in the deactivation of ZrO_2(H). Zhang et al. demonstrated that a hybrid network structure composed of biomass-derived carbon quantum dots and $ZrCl_4$-derived zirconia sol nanoparticles (2–5 nm) can be readily synthesized under mild dehydration conditions at low cost, utilizing these components as primary structural units [185]. Due to the enhanced Lewis acidity and stability of both Zr–O–Zr and Zr–O–C species, the proposed biomass carbon quantum dot–Zr network catalyst exhibited remarkable efficiency and stability for catalytic transfer hydrogenation in isopropanol, achieving up to 99.9% furfural conversion and 98.4% furfuryl alcohol yield under optimized conditions and maintaining high activity and selectivity even after five cycles. The raw materials are inexpensive and readily available, enabling scalable and cost-effective catalyst production, while also demonstrating resourceful utilization of biomass waste and advancing the development of high-performance catalysts. This study leverages the nanoarchitectonics concept by precisely assembling carbon quantum dots and zirconia nanoparticles to maximize catalytic performance. Structural control and interaction design provided by biomass carbon quantum dots enable stabilization of low-polymeric Zr–O–Zr species, formation of highly active sites, and suppression of side reactions—hallmarks of a nanoarchitectonics approach. Nanostructuring of waste biomass into functional materials leads to the creation of highly efficient, selective, and durable catalysts, marking a significant contribution to both materials science and green chemistry for sustainable applications.

The exploration of paramagnetic metal nanoparticles with atomic-level precision remains challenging due to difficulties in synthesis, which has hindered detailed studies of their paramagnetic properties. Bian et al. successfully achieved the precise synthesis and structural control of large paramagnetic gold nanoclusters using a thiol–iodine mixed-ligand methodology (Fig. 5) [186]. Their work demonstrated sequential control over magnetic states—via single-atom removal and oxidation—while revealing that surface spins are primarily localized on iodine atoms. Utilizing a thiol–iodine mixed-ligand protection strategy, they synthesized a multivalent shell structure: the paramagnetic $[Au_{127}I_4(TBBT)_{48}]$ (I = iodine, TBBT = 4-tert-butylphenylthiolate). The central gold atom could be selectively removed via thiol derivatization without collapsing the framework. Alterations

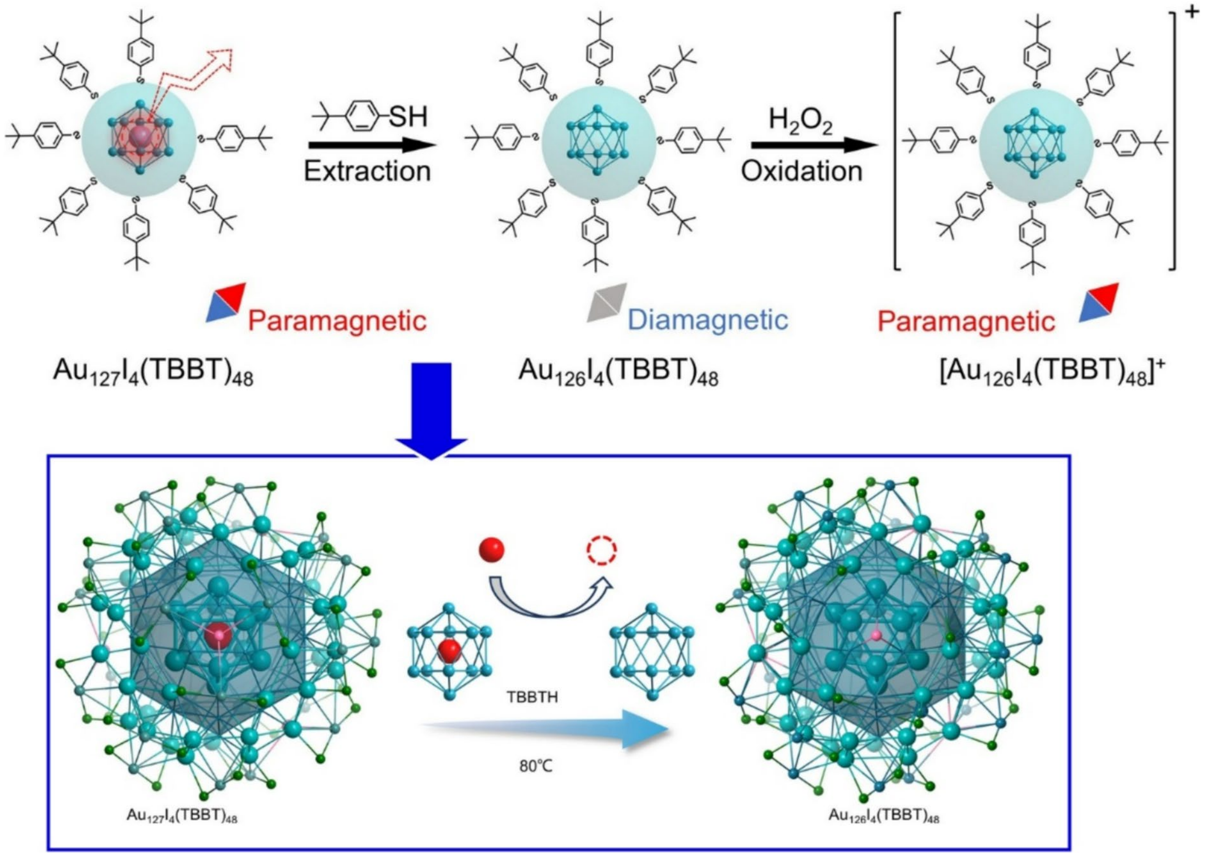


Fig. 5 Precise synthesis and structural control of large paramagnetic gold nanoclusters ([Au127I4(TBBT)48] (I = iodine, TBBT = 4-tert-butylphenylthiolate)) using a thiol–iodine mixed-ligand methodology through sequential control over magnetic states via single-atom removal and oxidation. Reprinted with permission from Ref. 186 Copyright 2025 AAAS

in the local ligand arrangement (the "butterfly effect") enabled conversion from paramagnetic to diamagnetic $Au_{126}I_4(TBBT)_{48}$, and further oxidation with H_2O_2 produced paramagnetic $[Au_{126}I_4(TBBT)_{48}]^+$. Structural modifications and electronic state control also allowed for tunable CO_2 electrocatalytic activity, highlighting a new approach to the design of magnetic and catalytic functions in nanoparticles. This study leverages nanoarchitectonics by enabling atomic- and electronic-level structural manipulation of gold nanoclusters to precisely tune their magnetic and catalytic properties. This includes ligand design for surface spin localization, atomically precise restructuring, and continuous property modulation through redox operations—all direct realizations of function creation from the molecular and nanoscale as envisioned by nanoarchitectonics. The capacity for free design of nanostructure and structure–property correlations makes a significant contribution to the development of high-value-added catalysts and magnetic materials.

Kiguchi et al. developed nanoscale magnetic photocatalysts (nano TiO_2–SiO_2/Fe_3O_4) with particle sizes of approximately 20 nm and applied them to efficient water treatment [187]. These magnetic nanophotocatalysts exhibited performance and stability comparable to commercial P25 photocatalysts, while enabling easy recovery from aqueous media via magnetic separation. The photocatalyst was employed for the photoinactivation of *Lactobacillus casei* (*L. casei*) as well as for the degradation of recalcitrant herbicides (simetryn, prometryn, metolachlor, and sulfosulfuron-methyl). *L. casei*, a Gram-positive bacterium lacking an outer membrane, was adopted as a model organism for photocatalytic antimicrobial evaluation;

complete sterilization was achieved within 50 min of UV irradiation, showing a simpler reaction profile compared to conventional Gram-negative models. The photocatalyst was also highly effective against the four herbicides, reducing their concentrations from 10 ppm to below 1 ppm within 120 min. These results underscore the potential of the nanocatalyst for large-scale water purification in the food and agricultural industries. In this study, the nanoarchitectonics framework enabled the simultaneous resolution of multiple challenges—including photocatalyst functionality, separability, and stability—through the rational design and assembly of nanoparticles. Integrating TiO_2–SiO_2 and Fe_3O_4 at the nanoscale imparted high catalytic efficiency, magnetic recoverability, and long-term stability. The precise design and self-organization of nanoparticles for multifunctionality exemplifies the power of nanoarchitectonics in the development of sustainable water purification materials, making substantial contributions to environmental and food safety.

Introducing OH interaction sites to accelerate water dissociation increases hydrogen coverage on the active surface, thereby promoting hydrogen spillover and enhancing the overall hydrogen evolution reaction (HER). While homologous nanometallic single-atom catalysts combining single atoms and nanometal particles have been developed, the synthesis of heterogeneous nanometallic single-atom catalysts remains challenging. For HER catalysts under alkaline conditions, ideal architectures require a synergistic effect between nonnoble metal nanoparticles with strong oxygen affinity and noble metal single atoms (SAs) with favorable hydrogen binding energies. Xu et al. developed a nanoparticle catalyst by encapsulating Co nanoparticles and Pt single atoms within N-doped hollow polyhedral carbon via a straightforward pyrolysis–encapsulation route (Fig. 6) [188]. This catalyst exhibited high activity and stability for the HER under alkaline conditions. The Co nanoparticles function as H-pumps, promoting hydrogen spillover to the Pt single-atom sites (from the C site → C–Pt bridge → Pt site), thereby boosting overall efficiency. This method offers practical prospects for the rational design of catalysts with tunable metal species and architectures. This study exemplifies the nanoarchitectonics approach by enabling precise structural and spatial control over Co nanoparticles and Pt single

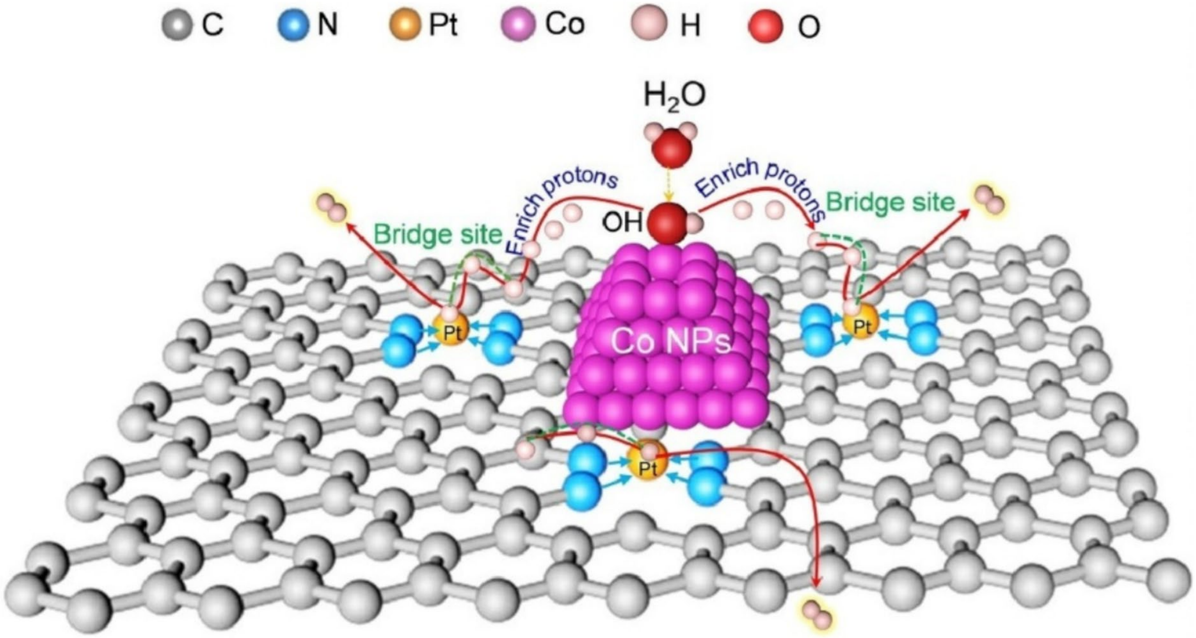


Fig. 6 A nanoparticle catalyst by encapsulating Co nanoparticles and Pt single atoms within N-doped hollow polyhedral carbon exhibiting high activity and stability for the HER under alkaline conditions. Reprinted with permission from Ref. 188 Copyright 2025 Wiley-VCH

atoms at the nanoscale to design and optimize chemical reaction pathways and functionalities. The composite arrangement and interaction modulation at the nanoscale facilitate efficient water dissociation and hydrogen transfer, representing a paradigmatic case of catalytic function creation via nanoarchitectonics. Precise tuning of metal species, size, and arrangement greatly contributes to the development of new, high-efficiency catalysts and sustainable energy materials.

In water electrolysis, nanoscale structural design of electrocatalysts and their supports is crucial for enhancing catalytic efficiency through overpotential reduction. Platinum (Pt), widely used as a cathodic catalyst for the HER, is costly, and thus, core–shell structures are often employed to minimize the required amount. Traditionally, Pt nanoparticles with diameters of 1–2 nm are uniformly dispersed on carbon black supports, forming typical core–shell architectures. Core–shell catalysts have been extensively studied, and various systematic modifications have been developed and evaluated. Notably, Park et al. proposed a reverse configuration—shell–core structures—where the catalyst serves as the core and the support as the shell. In their study, iridium (Ir) nanoparticles were encapsulated as the core by a mesoporous carbon shell, achieving comparable or superior HER performance to conventional catalysts with Ir contents of less than 1 wt% [189]. Unlike the conventional catalyst core/support shell paradigm, this inverted structure proved highly effective. The excellent dispersion of Ir nanoparticles and the high specific surface area contributed to the high efficiency, presenting a new design guideline for reducing the consumption of precious platinum-group metals while maintaining high catalytic performance. This work also underscores the importance of nanoarchitectonics. Precise nanoscale control over Ir nanoparticle size, dispersion, and spatial arrangement within the mesoporous carbon shell simultaneously optimizes catalytic activity and drastically reduces noble metal usage. Such precision in structural design and organization—enabled by nanoarchitectonics—affords tunability of active surface area, electronic conductivity, and interparticle interactions, opening new avenues for the development of sustainable, high-efficiency electrocatalyst materials.

In their paper titled “Nanoarchitectonics with Thiolate-Protected Ultrasmall Platinum Nanoclusters,” Shahul and Pandurangan reported the synthesis of ultrasmall platinum nanoclusters (Pt-NCs), each protected with one of three thiols—3-mercaptopropane sulfonic acid (MPS), 3-mercaptopropionic acid (MPA), and glutathione (GSH)—via a simple chemical reduction method [190]. Each thiolate-protected Pt nanocluster (Pt-MPS, Pt-MPA, and Pt-GSH) was synthesized successfully with precise atomic-level thiol protection, yielding sizes ranging from 1.2 to 4 nm. When incorporated into an ionic liquid matrix, these Pt nanoclusters exhibited high specific capacitance, enhanced stability, and excellent supercapacitive performance. Compared to conventional materials, these nanoclusters delivered superior performance and show promise for various energy storage applications. From the perspective of nanoarchitectonics, this study demonstrates that precise nanocluster design—such as careful choice of thiol and nanoscale size control—combined with integration into ionic liquid matrices can dramatically improve electrochemical properties and stability. Atomic-level surface protection and interface engineering are directly linked to the development of high-performance capacitive functions, providing an exemplary case of advanced energy material design and the expansion of application possibilities enabled by nanoarchitectonics.

As demonstrated by the above examples, nanoarchitectonics has made significant contributions to the advancement of energy applications by maximizing catalytic functionality through precise molecular- and nanoscale structural design and assembly. For instance, hybrid catalysts composed of biomass-derived carbon quantum dots and zirconia nanoparticles have achieved exceptionally high efficiency and durability in biomass conversion reactions by stabilizing catalytic sites and suppressing side reactions—capabilities enabled by nanoarchitectonics. In paramagnetic gold nanoclusters, ligand engineering and atomic-level rearrangement provide precise control over properties such as magnetism and CO_2 reduction activity, paving the way for the development of novel, high-performance catalysts. Further, in studies involving magnetic nanophotocatalysts, multimetallic single-atom catalysts, and shell–core-type electrocatalysts, the design of nanoscale structure, spatial arrangement, and heterogeneous material combinations has resulted in remarkable improvements in reaction efficiency, selectivity, material cost reduction, separability, and capacitance. These advances provide new design strategies and expanded applications for the development of high-efficiency, multifunctional catalytic materials—essential for sustainable energy production and resource recycling.

Sensing to environment

The importance of sensing technologies that support environmental preservation and safe, secure living is steadily increasing. With the diversification of industrial activities and living environments, there is a growing demand for the rapid assurance of food safety, water purification, and solutions to energy-related challenges. Addressing these issues necessitates the development of advanced material design and highly sensitive sensing technologies based on nanotechnology. In particular, the creation of new materials through nanoarchitectonics—precise structural control at the molecular and nanoscale—holds great promise for enhancing the performance of functional materials and achieving a sustainable society. This section presents recent trends in nanomaterials research from this perspective.

Aggregation-induced emission enhancement (AIEE) of metal nanoclusters has enabled numerous applications, including food safety monitoring. However, the controlled synthesis of monodisperse metal nanocluster supraparticles exhibiting AIEE properties remains challenging. In their paper, "Supraparticle Nanoarchitectonics with Bright Gold Nanoclusters," Li et al. reported a facile method for synthesizing gold nanocluster supraparticles (CB[n]/AuNCs) with AIEE properties via host–guest recognition involving cucurbit[n]uril (CB[n], $n=7$ and 8) and ATT molecules, specifically for food safety monitoring applications (Fig. 7) [191]. The resulting supraparticles exhibited significantly enhanced emission intensity and quantum efficiency (up to 52%), as well as sensitive response to pH and ammonia. These properties enabled their application in paper-based sensors for meat freshness determination. Utilizing this system, highly sensitive fluorescence turn-on detection of ammonia (detection limit 0.2 ppm) was achieved, and a fluorescent turn-on paper sensor was successfully fabricated for monitoring meat freshness. This approach offers a facile, controllable, and biocompatible synthetic strategy for AIEE-active metal nanoclusters, establishing a foundation for expanded performance and application potential. The host–guest recognition-based supraparticle strategy contributes both to enhanced fluorescent materials and their broad applicability. This research harnesses the nanoarchitectonics framework; surface ligand design and precise control over nanocluster aggregation states are achieved through host–guest interactions with cyclic compounds, resulting in efficient fluorescence performance and environmental responsiveness. This advanced nanoarchitectonics application illustrates how molecular recognition and supramolecular assembly at the nanoscale can create new sensing materials and enable novel developments in food safety monitoring.

Adenosine triphosphate (ATP) is a universal biomarker of cellular metabolism, and there is increasing demand for rapid and reliable point-of-care testing (POCT). However, conventional colorimetric biosensors often suffer from insufficient sensitivity and operational instability. In their paper "MOF Nanoarchitectonics for Ultrasensitive Point-of-Care Detection," Jin et al. developed a high-sensitivity biosensor by integrating ultrasmall Pt nanozymes into an ATP-responsive MOF surface layer through protein-template synthesis and biomimetic MOF design (Fig. 8) [192]. Upon ATP stimulation, the MOF matrix disassembles, releasing the Pt nanozyme and generating a strong colorimetric signal. This sensor addresses major limitations in ATP diagnostics by combining nano-bio-interfacial engineering with the biomimetic mineralization of MOFs and nanozyme catalysts. The Pt nanoclusters were synthesized and stabilized at room temperature using glucose oxidase as a template, achieving ultrasmall particle sizes (2.30 ± 0.52 nm) and suppressed aggregation, thereby ensuring a high density of catalytic active sites. Consequently, the oxidase-like activity of the Pt nanozyme was about four times higher than conventional products. These nanozymes were directionally immobilized within an ATP-degradable MOF layer, allowing ATP-specific nanoprobes to be prepared. Upon ATP stimulation, the MOF matrix breaks down, releasing the Pt nanozyme, which elicits a turn-on colorimetric response through enhanced oxidase-like catalytic reactions. This platform achieves ATP detection with a wide working range and an ultralow detection limit (0.062 μM), making practical ATP POCT diagnosis possible and laying the groundwork for next-generation multifunctional biosensors. This study exemplifies the nanoarchitectonics approach,

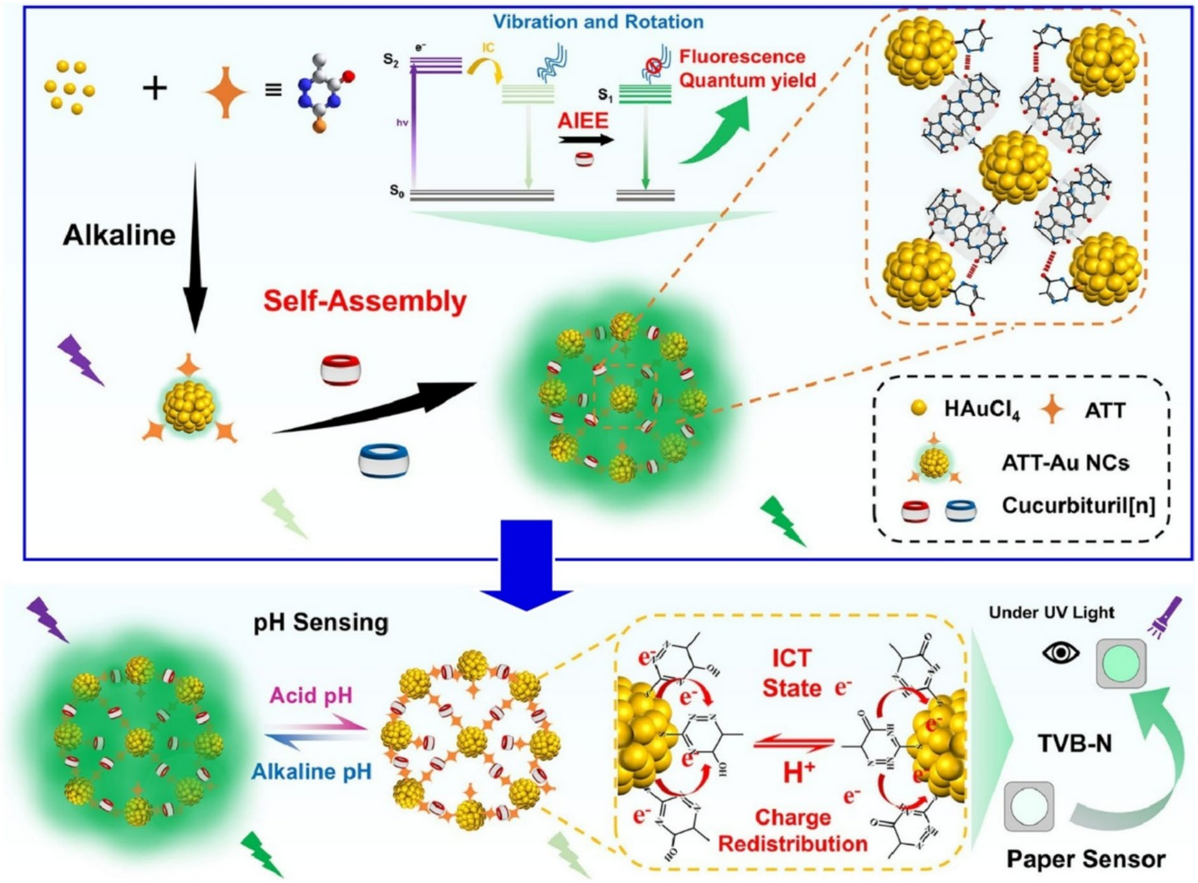


Fig. 7 Preparation of gold nanocluster supraparticles (CB[n]/AuNCs) with aggregation-induced emission enhancement (AIEE) properties via host–guest recognition involving cucurbit[n]uril (CB[n], $n=7$ and 8) and ATT molecules, useful as fluorescent turn-on paper sensor with sensitive response to pH and ammonia. Reprinted with permission from Ref. 191 Copyright 2025 American Chemical Society

where Pt nanocluster catalysts and MOF structures are precisely designed and integrated on the molecular and nanoscales to achieve highly functional, stable, and responsive biosensors. The protein-templated synthesis of nanozymes, MOF-derived surface control, and stimuli-responsive interfacial engineering are representative outcomes of nanoarchitectonics, demonstrating significant contributions to solving real-world challenges in clinical diagnostics and beyond.

Transition metal chromite nanoparticles are promising multifunctional materials for energy and environmental applications, owing to their tunable physicochemical properties. In their study titled “Nanoarchitectonics of $ZnCr_2O_4$ Nanoparticles,” Chakraborty and Jeevanandam reported a facile thermal decomposition method for the synthesis of $ZnCr_2O_4$ nanoparticles. Through this approach, various morphologies—including raspberry-like, porous, and hexagonal forms—can be achieved by simply adjusting the synthesis conditions [193]. Comprehensive characterization of composition, purity, magnetic properties, and photocatalytic activity was performed. The $ZnCr_2O_4$ nanoparticles were evaluated for photocatalytic removal of the toxic dye Amido Black 10B in water. Notably, the mixed-solvent method yielded the highest photocatalytic efficiency (94%) and largest surface area, with the catalytic activity shown to be morphology-dependent. Tailoring morphology and properties in this way broadens the material’s applicability for energy and environmental solutions. The described methodology is also adaptable to the

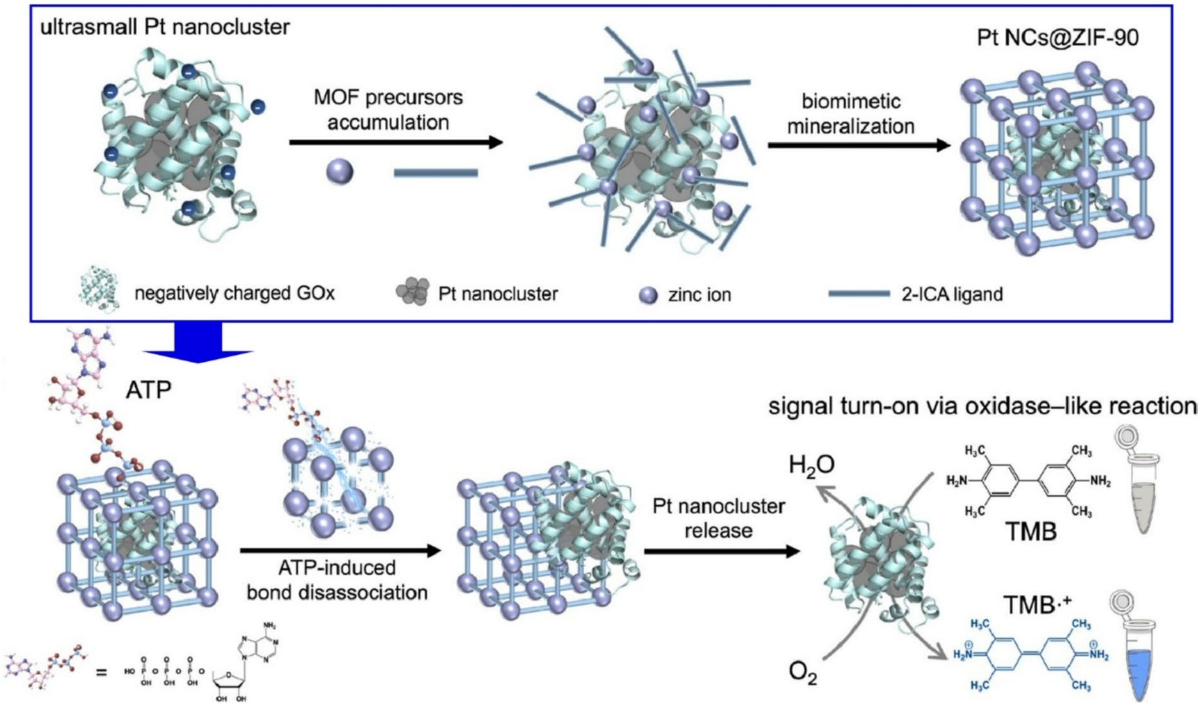


Fig. 8 Preparation of a high-sensitivity biosensor by integrating ultrasmall Pt nanozymes into an ATP-responsive MOF surface layer through protein-template synthesis and biomimetic MOF design. Reprinted with permission from Ref. 192 Copyright 2025 American Chemical Society

synthesis of other composite metal oxide nanomaterials. This research is rooted in the principles of nanoarchitectonics, enabling the precise design and optimization of nanoparticle properties and functions through controlled structural and morphological manipulation (such as solvent condition tuning). By adjusting the size, shape, and surface structure of $ZnCr_2O_4$ nanoparticles on the nanoscale, their photocatalytic and magnetic properties can be finely tuned, facilitating the creation of advanced materials for energy and environmental applications. This function-by-nanostructure approach makes a substantial contribution to the development of sustainable, high-performance, and versatile materials.

Electrochemical deionization (EDI) is a highly promising next-generation water treatment technology. Bismuth (Bi), with its high capacity and Cl^- selectivity, shows great potential as an anode material for EDI; however, severe volume expansion and pulverization lead to drastic deterioration in cycle performance. In their study entitled “Carbon Nanoarchitectonics with Bi Nanoparticle,” Wang et al. reported a straightforward thermal decomposition method using a Bi-based MOF precursor to synthesize Bi@C nanocomposites, where Bi nanoparticles are uniformly encapsulated within carbon layers (Fig. 9) [194]. The strong Bi–O–C interactions reinforce the interface between Bi and carbon, while the carbon encapsulation effectively buffers the stress from volume expansion. Consequently, this structure overcomes issues of expansion and pulverization, providing structural protection and enhanced conductivity via the carbon framework. Thanks to these advantages, the Bi@C composite demonstrated outstanding electrochemical capacitance. When used as an EDI anode paired with an activated carbon cathode, the material exhibited a Cl^- removal capacity of 133.5 mg/g. After 100 cycles, the Bi@C electrode retained 71.8% of its initial capacity—substantially outperforming a pure Bi electrode, which retained only 26.3%. These results underline the effectiveness of this structure as a design guideline for next-generation EDI electrode materials. Rooted in the principles of nanoarchitectonics, this study achieves long-term

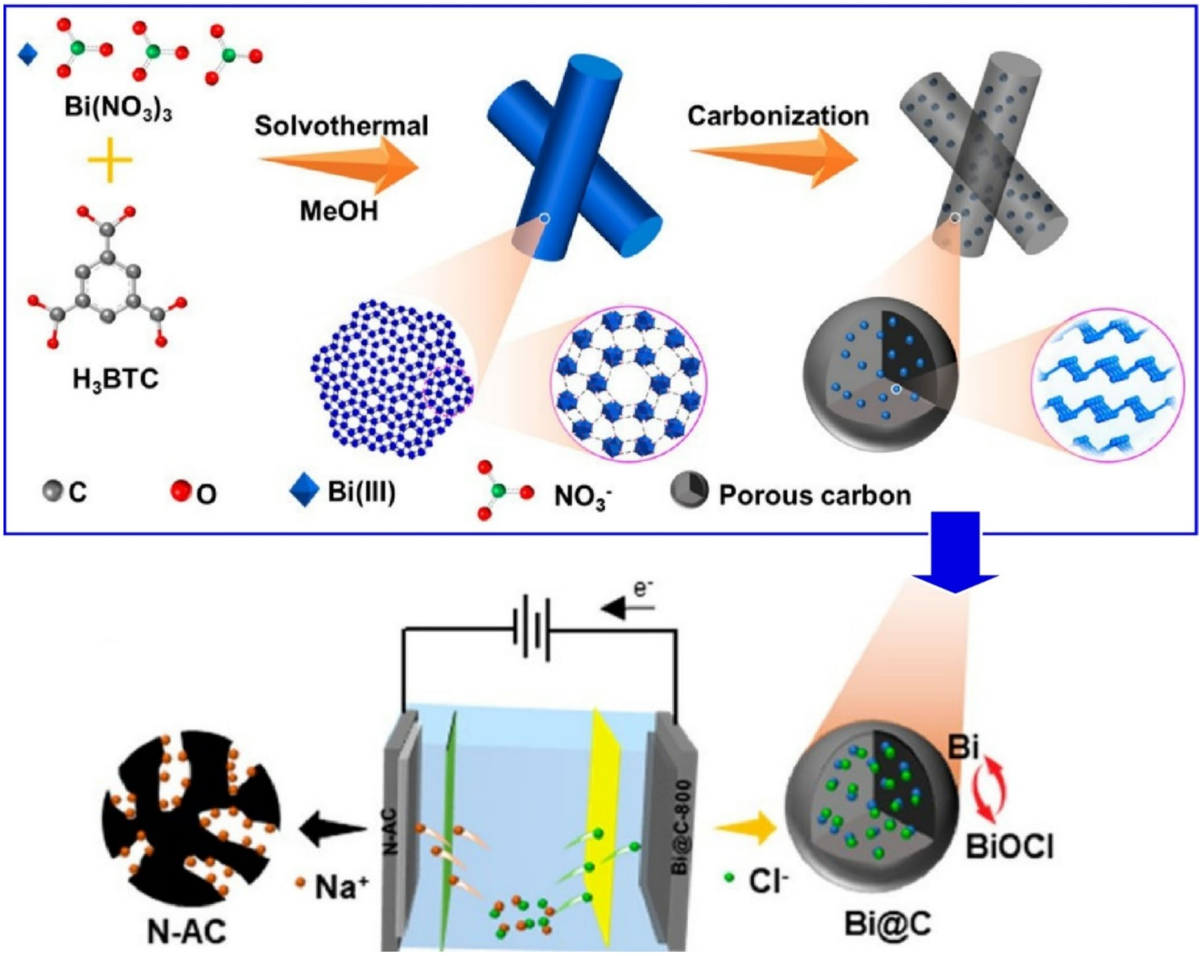


Fig. 9 A thermal decomposition method using a Bi-based MOF precursor to synthesize Bi@C nanocomposites, where Bi nanoparticles are uniformly encapsulated within carbon layers, used for electrochemical deionization as a promising next-generation water treatment technology. Reprinted with permission from Ref. 194 Copyright 2022 American Chemical Society

functionality through precise spatial arrangement of Bi nanoparticles and their integration with a carbon framework. This approach optimizes performance through nanoscale structural engineering and materials design, exemplifying typical outcomes of nanoarchitectonics—including the mitigation of volume changes and efficient ion removal—thereby making substantial contributions to the practical advancement of water treatment materials.

As illustrated by the examples presented in this section, the concept of nanoarchitectonics plays a crucial role in both sensing technologies and addressing environmental challenges. For instance, techniques that enable molecular-level control over the luminescence properties of metal nanoclusters have markedly advanced food safety measures, such as freshness monitoring and highly sensitive ammonia detection. Furthermore, functional materials designed at the nanoscale have been applied to the rapid and sensitive detection of biomarkers like ATP, as well as in the development of multifunctional biosensors for clinical environments. These achievements represent the outcomes of nanoarchitectonics, wherein the precise design of molecular and nanoparticle structures maximizes their intrinsic properties and responsiveness. In the environmental field, the rational design of nanomaterials—such as metal oxide nanoparticles and Bi-based nanocomposites—has made significant contributions to water purification technologies and the creation of sustainable energy materials. Such advanced methodologies not only enhance the performance of sensing materials and reduce environmental impact but also constitute an essential foundation for ensuring a safer and more secure society.

Biomedical

The application of nanoparticles in the medical field has brought remarkable innovations to both diagnostics and therapeutics. Through molecular-level structural design and surface modification, nanoparticles can achieve high biocompatibility, multifunctionality, and targeted delivery, enabling the integration of novel functionalities unattainable with conventional medical materials. In the biomedical arena in particular, nanoparticles have shown significant promise in diverse areas, including imaging diagnostics, drug delivery, and wound healing, with their importance and potential expected to grow further in the future. As illustrated by the examples in this section, research employing advanced nanoarchitectonics techniques continues to expand the range and impact of these biomedical applications.

Although a variety of medical imaging contrast agents have been developed, integrating contrast signal generation, therapeutic functions, and microrobotic capabilities within a single platform remains challenging without complex fabrication processes. Kim et al. developed a core–shell submicron particle system composed of upconversion nanoparticles (UCNPs) and a covalent organic framework (COF), termed UCNP–COF (Fig. 10) [195]. These core–shell UCNP–COF particles seamlessly integrate multispectral optoacoustic tomography (MSOT) imaging, drug loading with controlled release, and

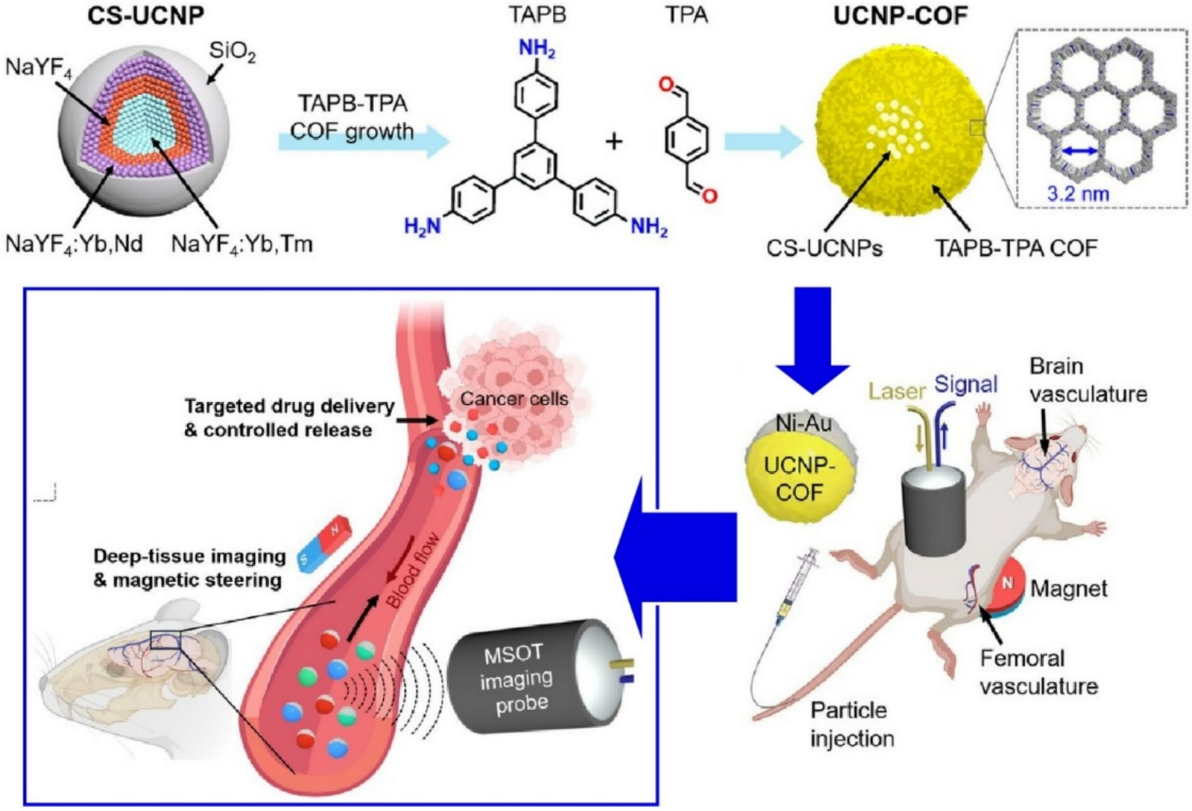


Fig. 10 Preparation and functions of a core–shell submicron particle system composed of upconversion nanoparticles (UCNPs) and a covalent organic framework (COF), to seamlessly integrate multi-spectral optoacoustic tomography (MSOT) imaging, drug loading with controlled release, and microrobotic functionalities for diagnostic–therapeutic technologies. Reproduced under terms of the CC-BY license from Ref. 195, 2025 Wiley-VCH

microrobotic functionalities. The COF shell enables efficient absorption of the UCNP-generated luminescence, conversion to acoustic signals for imaging, and offers high stability and biocompatibility. The regular mesoporous structure of the COF facilitates efficient drug encapsulation and controlled release at target sites. By incorporating a magnetic Janus layer, magnetic navigation and real-time tracking become possible, establishing a novel multifunctional platform for combined medical imaging and therapy. UCNP–COF particles act as therapeutic microrobots traceable by MSOT imaging and can be flexibly loaded with therapeutic molecules tailored to the intended application. The optoacoustic signal generation mechanism is based on upconverted emission from the UCNPs absorbed by the COF, which is subsequently converted into acoustic signals. Additionally, the mesoporous and high surface area characteristics of the COF enable efficient drug loading and controlled release specifically at targeted locations. By integrating a magnetic nanofilm, the UCNP–COF particles are transformed into magnetically responsive Janus microrobots that can be navigated intravascularly and tracked in real time via 3D MSOT. This research exemplifies the nanoarchitectonics approach, in which the precise assembly of heterogeneous nanomaterials—UCNPs and COFs—results in a single particle that synergistically integrates multiple functionalities, including luminescence, absorption, drug loading, magnetic manipulation, and biocompatibility. Nanostructural and interfacial design, combined with controlled porosity at the nanoscale, enables the manifestation of advanced chemical and physical functions, making significant contributions to the creation of next-generation multifunctional medical materials and diagnostic–therapeutic technologies through nanoarchitectonics.

Stiffness, a critical physicochemical property of nanoparticles, profoundly affects bio-nano-interactions such as blood circulation, biodistribution, tumor accumulation, and cellular uptake. However, the influence of stiffness on drug delivery efficiency remains to be fully elucidated. In their study titled "Multilayered Nanoarchitectonics of Poly(ethylene glycol) Nanoparticles," Li et al. tuned the stiffness of poly(ethylene glycol) (PEG) nanoparticles by controlling the number of layers and demonstrated that softer nanoparticles exhibited enhanced blood circulation, tumor accumulation, and cellular targeting, as well as reduced protein adsorption and hepatic accumulation (Fig. 11) [196]. In this work, PEG nanoparticles were synthesized using a layer-by-layer (LbL) assembly approach, and stiffness (Young's modulus ranging from 2 to 31 kPa) was adjusted by varying the number of bilayers. The results revealed that softer PEG nanoparticles exhibited lower protein corona formation and cellular adhesion and that increased stiffness (more layers) led to shorter circulation times and increased hepatic accumulation. Furthermore, stiffness significantly influenced targeted drug delivery; hyaluronic acid–modified soft PEG nanoparticles showed superior tumor accumulation, cellular targeting, and tumor growth inhibition. Thus, hyaluronic acid–functionalized soft nanoparticles demonstrated strong antitumor efficacy, highlighting the potential of optimizing drug delivery through control of nanoparticle stiffness and bio-nano-interactions. These findings underscore the crucial role of bilayer-controlled stiffness in regulating bio-nano-interactions and demonstrate the potential for more effective nanocarrier design in drug delivery applications. Employing the nanoarchitectonics concept, this study precisely engineered the layer structure and mechanical properties of PEG nanoparticles to optimize in vivo interactions and drug delivery performance. Integrating nanoscale physical properties, surface engineering, flexibility, and targeting epitomizes an innovative approach for adjusting biocompatibility, circulation, and therapeutic outcomes, firmly establishing the importance of nanoarchitectonics in the realization of high-performance nanocarriers.

The rise of multidrug-resistant wound infections necessitates novel therapeutic strategies that simultaneously eradicate pathogens while harmonizing the complex immune-healing processes. In their paper, "Green-nanoarchitectonics for Sub-2 nm Ag Nanoparticles," Li et al. developed a multifunctional cryogel by immobilizing ultrasmall silver nanoparticles onto attapulgite (APT) nanorods via green synthesis mediated by peony root extract and embedding these nanocomposites into a composite matrix (Fig. 12) [197]. Their green approach employed peony root extract to mediate the in situ formation and high dispersion of ultrasmall Ag nanoparticles (average 1.26 ± 0.3 nm) on APT nanorods. The resulting Ag nanoparticles/APT nanocomposites were then integrated into a physically crosslinked network of carboxymethyl chitosan (CMC) and

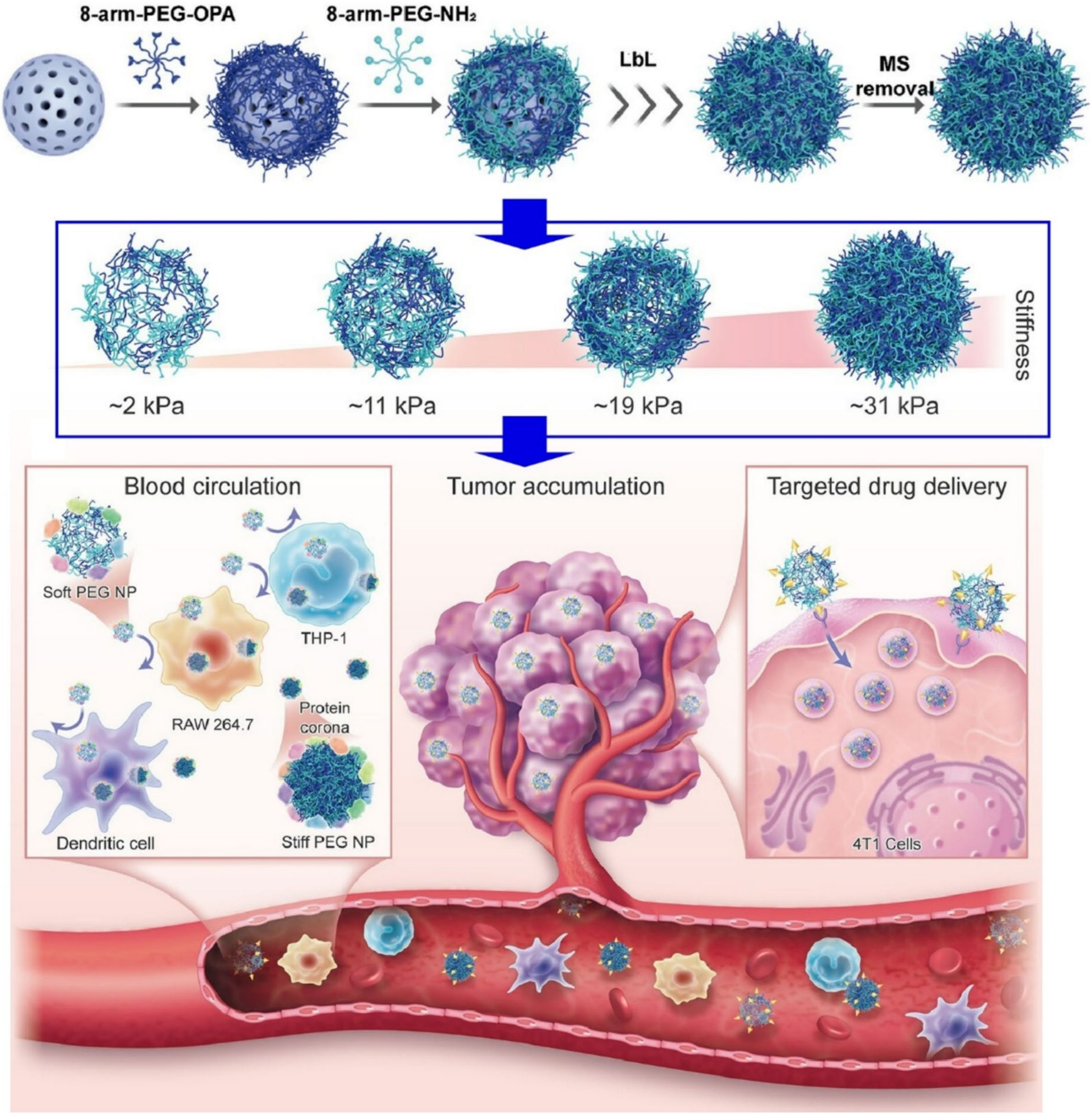


Fig. 11 Tuning of the stiffness of poly(ethylene glycol) (PEG) nanoparticles by controlling the number of layers, which demonstrated that softer nanoparticles exhibited enhanced blood circulation, tumor accumulation, and cellular targeting, as well as reduced protein adsorption and hepatic accumulation. Reprinted with permission from Ref. 196 Copyright 2025 American Chemical Society

κ-carrageenan (KCG), yielding a multifunctional cryogel (CMC/KCG/Ag nanoparticles/APT). This cryogel exhibited potent antibacterial activity against multidrug-resistant bacteria and biofilms, excellent mechanical strength, rapid liquid absorption, and high biocompatibility. The APT nanorods played a crucial role in both imparting strength to the polymer matrix and promoting the formation of ultrasmall silver nanoparticles. The incorporation of Ag nanoparticles/APT generated synergistic physicochemical effects—such as hydrogen bonding with CMC/KCG and mechanical interlocking—which

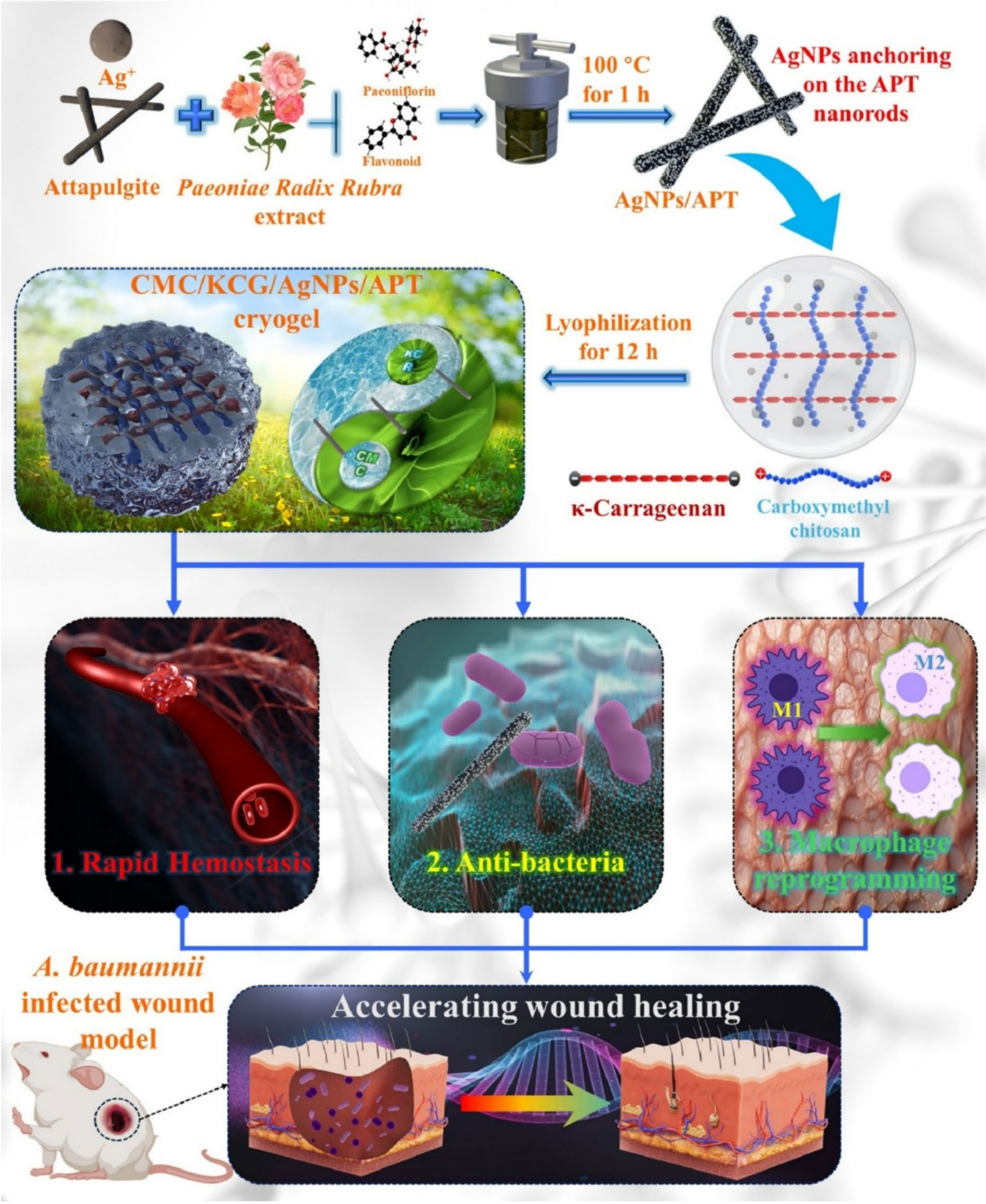


Fig. 12 Preparation of multifunctional cryogels by immobilizing ultrasmall silver nanoparticles onto attapulgite (APT) nanorods via green synthesis exhibiting potent antibacterial activity against multidrug-resistant bacteria and biofilms, excellent mechanical strength, rapid liquid absorption, and high biocompatibility for the development of wound management. Reprinted with permission from Ref. 197 Copyright 2025 American Chemical Society

provided a balance of high mechanical robustness and rapid hemostasis as the basis of the material's multifunctionality. The system achieved high antibacterial, hemostatic, and mechanical performance alongside inflammation modulation and tissue repair promotion, resulting in excellent healing rates for multidrug-resistant wounds. The synergistic integration of inorganic nanomaterials, biopolymers, and natural clay considerably advances the development of wound management materials. This study demonstrates the nanoarchitectonics approach by precisely assembling diverse constituents—including ultrasmall Ag nanoparticles, natural APT, and biopolymers (CMC, KCG)—at the nanoscale, enabling the simultaneous manifestation of antibacterial, hemostatic, mechanical, and immunomodulatory functions. The controlled structure and cooperative design transcend conventional material limitations, offering a sustainable and high-performance wound management solution—an exemplary outcome of nanoarchitectonics applied to multifunctional therapeutic material development.

Neurodegenerative diseases are prevalent, progressive, and fatal disorders particularly affecting the elderly. Many therapeutic candidates have failed due to insufficient efficacy, toxicity, or poor permeability across the blood–brain barrier, highlighting the need for improved drug delivery strategies. Nanomedicine offers a promising approach to enhance the therapeutic performance of existing compounds. In their study "Mesoporous Silica Nanoparticles via Template Nanoarchitectonics," Onrubia-Márquez et al. designed a nanoscale formulation of the metal-chelating drug deferoxamine (DFO) using mesoporous silica nanoparticles (Fig. 13) [198]. By conjugating hydrophobic chains to DFO to confer amphiphilic properties, DFO was used as a drug-structure-directing agent, enabling it to serve as a template for mesoporous silica nanoparticle formation. This strategy enabled the synthesis of mesoporous silica nanoparticles with high drug loading capacity, controlled release, and tunable particle size. The resulting nanoparticles exhibited efficient iron chelation and inhibition of aluminum-induced amyloid formation and

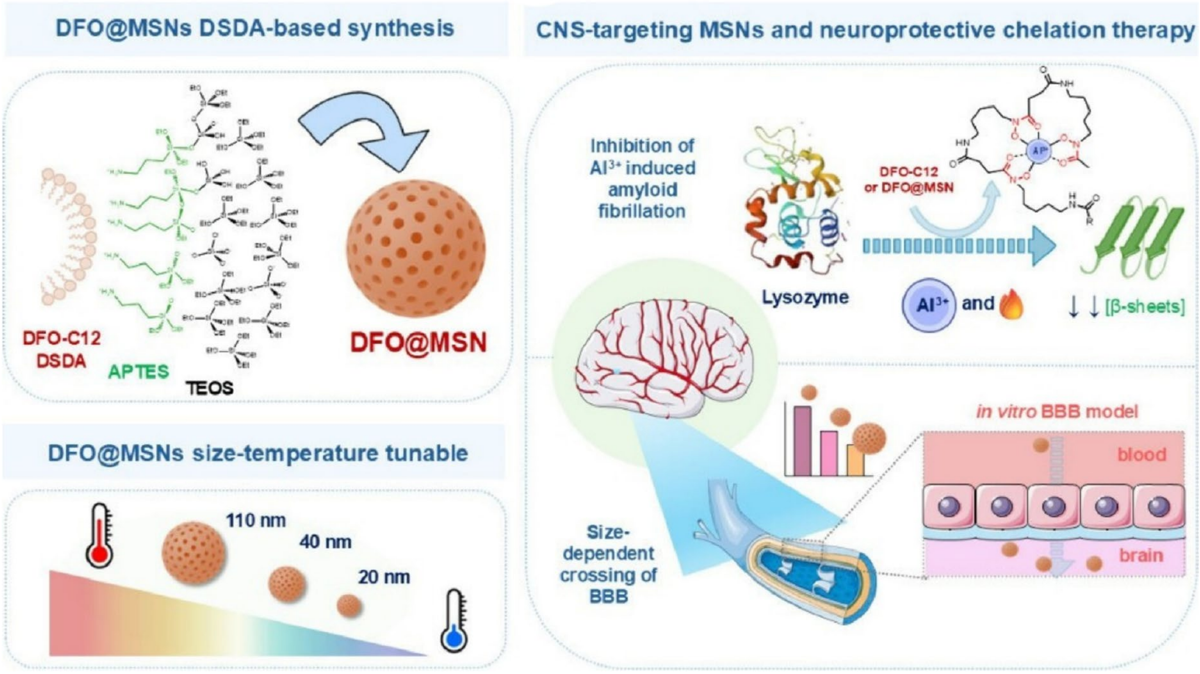


Fig. 13 Formulation of the metal-chelating drug deferoxamine (DFO) using mesoporous silica nanoparticles with particle size-dependent permeability across the blood–brain barrier in vitro, leading to a multifunctional, long-acting, and safe nanocarrier design for neurodegenerative diseases. Reproduced under terms of the CC-BY license from Ref. 198, 2025 American Chemical Society

demonstrated particle size–dependent permeability across the blood–brain barrier in vitro. Safety was confirmed using BV-2 microglia and human neuroblastoma SH-SY5Y cells, along with validation of iron chelation and aluminum-induced amyloid aggregation inhibition in vitro. This approach represents a multifunctional, long-acting, and safe nanocarrier design for neurodegenerative diseases, with further in vivo evaluation anticipated. This work exemplifies the nanoarchitectonics concept, wherein DFO derivatives function as structure-directing agents, enabling precise nanoscale control over mesoporous silica nanoparticle size, surface characteristics, drug encapsulation, and release profiles. Achieving high drug loading, sustained release via nanostructuring, and optimized bio-barrier permeability via particle size control are paradigmatic of function and performance creation through nanoarchitectonics—making a substantial contribution to the safe and multifunctional neuroprotective material development field.

VIPR2 is a receptor associated with psychiatric disorders, breast cancer metastasis, and cancer immunostimulation. The VIPR2 antagonist KS-133 shifts macrophage polarization toward the M1 phenotype, and nanoparticles releasing KS-133 exhibit antitumor effects against murine colon cancer cells (CT26). In the study titled "Therapeutic Nanoarchitectonics for Solid Tumors," Sakamoto et al. sought to enhance the antitumor effect of KS-133 nanoparticles by combining them with the peptide KS-487, which targets LRP1 expressed on CT26 cells [199]. By incorporating both the VIPR2 antagonist KS-133 and the LRP1-targeting peptide KS-487 into nanoparticles, they achieved substantially improved tumor delivery and antitumor efficacy in a murine CT26 colon cancer model. While the nanoparticles naturally accumulate in tumors via the enhanced permeability and retention (EPR) effect, the addition of the targeting peptide further increased accumulation at the tumor site. This dual-targeting approach resulted in greater infiltration of $CD8^+$ T cells and macrophages into tumor tissue, leading to enhanced antitumor immune activation and significant tumor suppression. The KS-133/KS-487 nanoparticle system represents a promising new antitumor agent, with potential applications in refractory cancer and in combination with immunotherapy. This work exemplifies the principles and technological advances of nanoarchitectonics by integrating functional peptide targeting (KS-487), VIPR2 antagonist delivery (KS-133), and nanoparticle engineering at the nanoscale. High tumor accumulation, immune cell activation, and efficient drug release were all achieved through precise nanostructural design. Such sophisticated control over nanoparticle surfaces, drug loading, and molecular modifications demonstrates the core of nanoarchitectonics, contributing significantly to the development of novel therapeutics for refractory cancers.

The treatment of pancreatic cancer remains challenging due to pronounced desmoplasia and severe hypoxic conditions. Unlike oxygen-dependent Type II photosensitizers, Type I photosensitizers can generate substantial amounts of reactive oxygen species (ROS) even under hypoxic conditions, making them suitable for photodynamic therapy (PDT) in pancreatic cancer. However, the highly dense extracellular matrix of pancreatic tumors hinders photosensitizer penetration, while immunosuppressive cells within the tumor microenvironment further diminish treatment efficacy. To address these challenges, Xu et al. designed a photoimmunotherapeutic nanoparticle system that combines a Type I photosensitizer with anti-PD-L1 siRNA (siPD-L1) encapsulated within M1 macrophage-derived membrane vesicles (Fig. 14) [200]. This system is tailored to operate in hypoxic and densely fibrotic tumor environments. In this design, pyropheophorbide a is covalently conjugated to poly-L-arginine, functioning as a Type I photosensitizer capable of generating superoxide anions efficiently even under hypoxia. Additionally, the Arg9 segment serves as a nitric oxide (NO) donor, inhibiting cancer-associated fibroblast activation and promoting extracellular matrix degradation, thereby improving nanoparticle penetration. The M1 macrophage membrane component contributes to active tumor targeting and facilitates the re-education of immunosuppressive M2 macrophages. Collectively, this system achieves enhanced NO production, improved tumor penetration through extracellular matrix modulation, reprogramming of the immunosuppressive environment, and augmented immunotherapeutic efficacy, ultimately yielding superior therapeutic effects in pancreatic cancer models. This represents a novel strategy underscoring the importance of oxygen-independent PDT and tumor microenvironment remodeling. The study exemplifies the nanoarchitectonics approach by precisely integrating diverse functional molecules and nanostructures—including Type I photosensitizers,

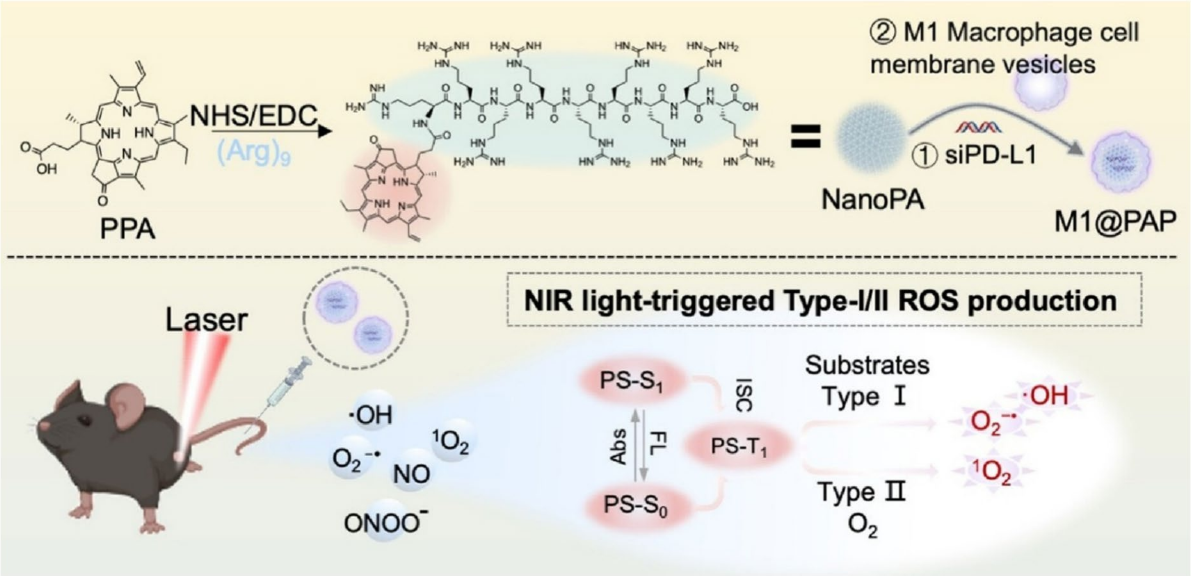


Fig. 14 Preparation of photoimmunotherapeutic nanoparticle system that combines a Type I photosensitizer with anti-PD-L1 siRNA (siPD-L1) encapsulated within M1 macrophage-derived membrane vesicles. Reprinted with permission from Ref. 200 Copyright 2025 American Chemical Society

NO donors, RNA therapeutics, and macrophage membranes—into a multifunctional platform through rigorous structural and interfacial design. Achieving biocompatibility, environmental responsiveness, and multifunctional therapeutic action via nanoscale engineering highlights the potential of nanoarchitectonics in enabling advanced drug delivery, tumor microenvironment modulation, and reinforced immune activity in cancer therapy.

Ischemic stroke is a devastating disorder and one of the leading causes of death worldwide. Excessive generation of ROS and inflammatory responses following ischemic injury contribute significantly to secondary brain damage. Although nanozymes with potent antioxidative properties have shown promise for treating ischemic injury, their limited accumulation within neuronal mitochondria has hindered clinical translation. In their study titled “Polydopamine-Cloaked Nanoarchitectonics of Prussian Blue Nanoparticles,” Zhao et al. developed polydopamine-coated Prussian blue nanoparticles endowed with antioxidant and anti-inflammatory functions for ischemic stroke therapy (Fig. 15) [201]. These nanoparticles achieved targeted accumulation in neuronal mitochondria and exhibited potent antioxidative and anti-inflammatory effects. In neonatal and adult mouse models, they demonstrated enhanced brain accumulation, reduced infarct volume, neuroprotection, attenuation of inflammation, and promoted functional recovery—pointing toward their potential as multifunctional nanomaterials for the treatment of brain disease. This study utilizes the framework of nanoarchitectonics by precisely engineering particle size, surface coating, and functional properties (antioxidant activity, anti-inflammatory capability, and mitochondrial targeting) to optimize brain accumulation and therapeutic performance. Structural, molecular, and interfacial designs at the nanoscale have led to significant advances in neurodegenerative disease therapy and hold promise for the creation of next-generation multifunctional nanomaterials.

As demonstrated in the examples above, nanoarchitectonics has driven numerous innovations in the biomedical applications of nanoparticles. Traditionally, single-function contrast agents or carriers dominated medical practice; however, recent studies have enabled the precise integration of heterogeneous nanomaterials to create particle designs that unify multiple functionalities—including imaging diagnostics, drug loading, and microrobotic capabilities—within a single platform. Moreover, the molecular-scale optimization

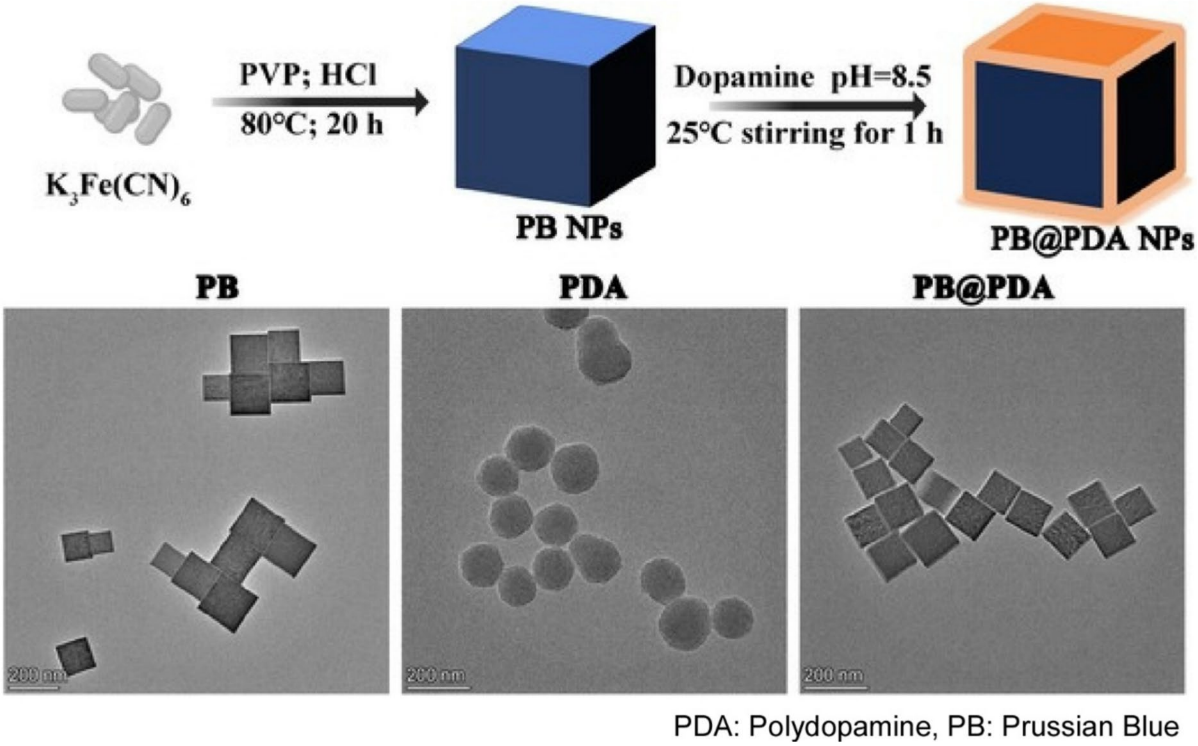


Fig. 15 Preparation of polydopamine-coated Prussian blue nanoparticles endowed with antioxidant and anti-inflammatory functions for ischemic stroke therapy and their TEM images. Reproduced under terms of the CC-BY license from Ref. 201, 2024 AAAS

of nanoparticle stiffness, multilayer structure, and surface modification has markedly improved biodistribution and targeting efficacy in vivo. Such advances contribute to the development of multifunctional nanomaterials that achieve both therapeutic efficacy and safety in previously intractable areas, such as refractory tumors, neurological disorders, and multidrug-resistant wound infections. Progress in environmentally friendly synthesis through green nanoarchitectonics and the targeted delivery of nanoparticles for brain diseases exemplifies the adaptability of this approach. Nanoarchitectonics thus provides an essential foundation for designing high-performance medical materials, customizable to the characteristics and therapeutic challenges of specific diseases. The convergence of nanotechnology and nanoarchitectonics is accelerating the emergence of advanced diagnostic and therapeutic modalities in next-generation biomedical science.

Summary and outlook

As summarized in this article, the concept of nanoarchitectonics has become indispensable in the development of functional nanoparticles. Nanoarchitectonics is a design philosophy that enables the creation of materials with novel functions and properties unattainable by traditional materials science, through the precise control and integration of atoms, molecules, and nanoscale structures. One of the primary application areas for functional nanoparticles is the energy and environmental fields. The advancements have enabled significant progress in addressing multifaceted challenges such as improvements in energy conversion efficiency, resource recycling, water purification, and the enhancement of sensor functionality. The contributions of nanoarchitectonics with functional nanoparticles in the bio- and medical fields have also become remarkable. In applications such as medical imaging agents, drug delivery systems, microrobotic interventions, regenerative medicine, and wound healing biomaterials, advances in precise structural design—such as multifunctional core–shell particles, stiffness-tuned nanoparticles, green cryogels for multidrug-resistant bacteria, and mesoporous silica nanocarriers—have enabled the realization of high biocompatibility, targeted delivery, and multifunctionality. Moreover, in the field of sensing and diagnostics, the development of highly sensitive biosensors and food safety monitoring materials has been realized through the rational design of nanoparticles and nanoclusters. As evidenced by leading-edge cases in each field, the creation and expanding application of functional nanoparticles epitomizes the progress of "design science" enabled by the principles and techniques of nanoarchitectonics, positioning it at the core of materials innovation for a sustainable society. In addition to these contents, recent several review articles on nanoarchitectonics and nanoparticles approaches for catalytic functions would provide further information. For example, their critical importance on enzyme biocatalysis in pharmaceuticals [202], peptide-nanoparticle conjugates as a theranostic platform [203], and all solid-state batteries [204] is deeply discussed.

As outlined above, nanoarchitectonics is being increasingly applied to a diverse array of substances and functional systems, and the field is witnessing remarkable innovations in the development of functional nanoparticles. Looking ahead, the integration of artificial intelligence (AI) and materials informatics stands out as a particularly promising direction. AI and machine learning have already been introduced in many studies and will become indispensable for the precise design and prediction of diverse functional molecules and structures at the nanoscale [205–208]. Rational implementation of complex functionalities—such as those mimicking biological tissues—will increasingly require AI-driven design support, optimization, and the fusion of materials informatics with nanoarchitectonics [209–213].

The research focus within nanoarchitectonics is also shifting toward practical applications, with advances in technologies for the large-scale and high-area fabrication of functional nanoparticles. This trend reflects a move to incorporate existing production process technologies, such as chemical processing and microfabrication, thereby translating nanoarchitectonics concepts into industrial practice. These developments are bridging the gap between academic knowledge and practical implementation and are expected to advance the high-performance, cost-effectiveness, and mass production of functional nanoparticles for broader societal use.

Going forward, the design and development of complex nanoparticles composed of multiple functional units—such as composite nanoparticles—will become increasingly important. To this end, optimization and simulation techniques supported by AI are anticipated to be utilized more extensively than ever before. In summary, the development of functional nanoparticles via nanoarchitectonics, in conjunction with AI, materials informatics, and practical process technologies, is expected to spur new breakthroughs and expand industrial applications. This trend will accelerate the rational design of multifunctional and composite nanoparticles, driving the future advancement of materials science and nanotechnology.

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Data availability No datasets were generated or analyzed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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