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REVIEW

Composite Nanoarchitectonics Towards Method for Everything in Materials Science

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Abstract
The characteristic feature of a biofunctional system is that components with various functions work together. These multi-components are not simply mixed together, but are rationally arranged. The fundamental technologies to do this in an artificial system include the synthetic chemistry of the substances that make the component unit, the science and techniques for assembling them, and the technology for analyzing their nanoostructures. A new concept, nanoarchitectonics, can play this role. Nanoarchitectonics is a post-nanotechnology concept that involves building functional materials that reflect the nanostructures. In particular, the approach of combining and building multiple types of components to create composite materials is an area where nanoarchitectonics can be a powerful tool. This review summarizes such examples and related composite studies. In particular, examples are presented in the areas of catalyst & photocatalyst, energy, sensing & environment, bio & medical, and various other functions and applications to illustrate the potential for a wide range of applications. In order to show the various stages of development, the examples are not only state-of-the-art, but also include those that are successful developments of existing research. Finally, a summary of the examples and a brief discussion of future challenges in nanoarchitectonics will be given. Nanoarchitectonics is applicable to all materials and aims to establish the ultimate methodology of materials science.

Keywords Nanoarchitectonics · Composite · Energy · Environmental · Biomedical

1 Introduction

Biological systems that has a highly sophisticated structures and perform efficient and highly selective functions can be said to be the ultimate forms of functional material systems. The characteristic feature of a bio-functional system is that components with various functions work together [1–3]. These multi-components are not simply mixed together, but are rationally arranged. Their organizational structures are hierarchical and asymmetrical. Accordingly, material and information transformations are performed continuously and sequentially. Energies are integrated and electrons flow vectorially. This is a highly evolved form of functional material system. It can also regarded as a highly organized composite system. The goal of material chemistry for functional materials is to construct such material systems.

Highly functional composites should not be merely mixed with ingredients. It is organized with extreme precision. The fundamental technologies to do this in an artificial system include the synthetic chemistry of the substances that make the component units, the science and techniques for assembling them, and the technology for analysing their nanostructures. Humanity has developed those elemental technologies. Organic chemistry [4–8], inorganic chemistry [9–13], coordination chemistry [14–18], polymer chemistry [19–23], material chemistry [24–28], and biochemistry [29–33] are still being developed as creating units or substances. Methodologies such as self-assembly by supramolecular chemistry [34–37] are used to bring them in organization. Thin film technologies such as self-assembled monolayer (SAM) [38–42], Langmuir-Blodgett (LB) method [43–47], layer-by-layer (LbL) assembly [48–52] are also used. Synthesis of ordered porous materials such as metal-organic

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frameworks (MOFs) [53–57], covalent organic frameworks (COFs) [58–62], mesoporous materials [63–67] is also useful. Not limited to these typical materials forms, various integrated structures are used for advanced functions including sensors [68–72], devices [73–77], batteries [78–82], fuel cells [83–87], solar cells [88–92], supercapacitors [93–97], and so on. Engineering fabrication techniques such as lithography also have a wide range of applications [98–102]. Even more important is the technology to analyse nanostructures. An important contribution is made by a series of technologies featured in nanotechnology [103–105]. These include structural observation at the atomic and molecular level [106–109], manipulation [110–113], and evaluation [114–117] of physical properties at the nanoscopic level. Integrating all of these technologies to create materials is essential for constructing advanced functional material systems.

A new concept, nanoarchitectonics, can play this role (Fig. 1) [116–121]. Nanoarchitectonics can be considered as post-nanotechnology [122, 123]. Just as Richard Feynman initiated nanotechnology in the mid-20th century [124, 125], Masakazu Aono proposed nanoarchitectonics in the early 21st century [126, 127]. Nanoarchitectonics is an interdisciplinary concept rather than an entirely new concept. It has the role of developing a group of functional materials that rationally reflect the nanostructure by integrating the existing material science with the nanoscale science/technology of nanotechnology. The functional material system will be built from units such as atoms, molecules, and nanomaterials, taking advantage of the characteristics of nanostructures [128, 129]. The process uses elements such as atomic and molecular manipulation, physical and chemical material transformation, self-assembly/self-organization, alignment and organization by external fields and actions, biochemical processes, and nano and micro fabrication techniques [130]. These elemental technologies are selected and combined to architect materials from nano.

This methodology is widely applied regardless of the material used or its intended application. For example, recent papers advocating nanoarchitectonics can be found in a wide range of fields. In addition to application-oriented areas such as catalysis [131–135], sensors [136–140], devices [141–145], energy production [146–150], energy storage [151–155], environmental response [156–160], drug delivery [161–165], and biomedical applications [166–170], there are also fundamental areas such as material synthesis [171–176], structural control [177–181], the exploration of physical phenomena [182–186], relatively basic biochemical studies [187–191], and research on cellular interactions [192–196]. Since all matter is principally composed of atoms and molecules, the methodology of building matter from atoms and molecules is applicable to all material synthesis. It could be likened to the ultimate theory of everything in physics [197], and nanoarchitectonics could be called a method for everything in materials science [198, 199]. This concept of nanoarchitectonics, which is applicable to all materials, is more suitable for the construction of multi-component functional material systems such as composites.

Now, the ideal functional material is to create complex composites like biological systems. To achieve advanced functionality, the components must be rationally organized, rather than simply a collection of functional molecular units. Their structure is asymmetric and hierarchical. The process flows accordingly in a continuous and directional manner. In assembling such hierarchical structures, nanoarchitectonics has advantages [200]. In nanoarchitectonics, materials are built by combining several unit processes. Therefore,

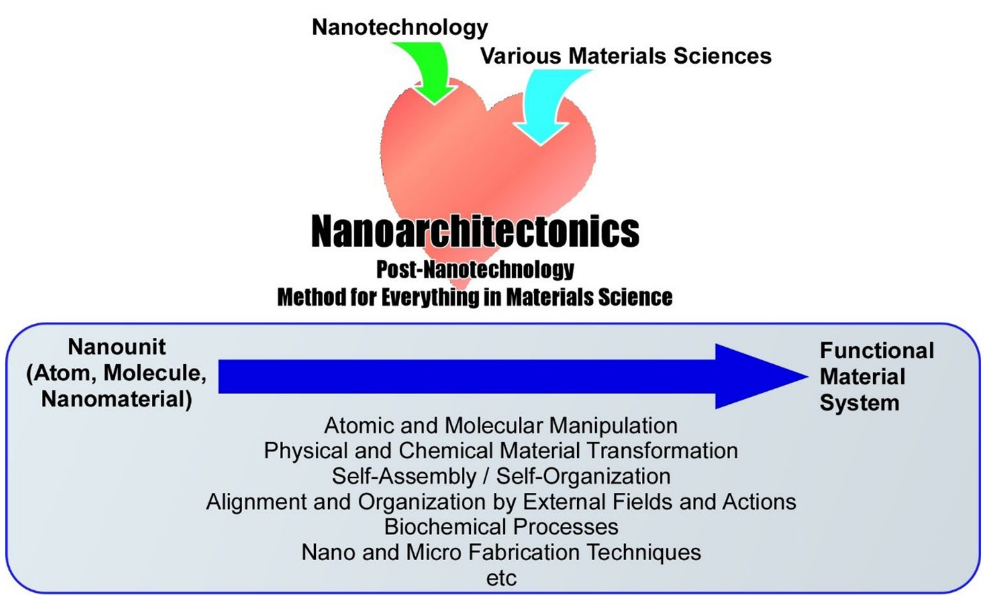

Fig. 1 Outline of nanoarchitectonics concept: meaning and procedure

nanoarchitectonics approaches easily create hierarchical structures than self-assembly by simple equilibrium processes [201]. It also has an aptitude for incorporating multiple components. Another feature is the harmonization of actions. It is nano interactions that are the origin of nanoarchitectonics. There is a degree of uncertainty involved [202]. In the nano processes of nanoarchitectonics, uncertainties such as thermal fluctuations, stochastic distributions, and quantum effects can be included. Thus, many effects will not simply add up, but will work in a jointly harmonized manner [203]. This is similar to what happens in bio-functional research, where many effects harmonize with each other to achieve advanced functionality. If the goal is to develop highly functionalized composite materials, it is necessary to incorporate such harmonization of actions.

Combining the concept of nanoarchitectonics with multicomponent composites can lead to the architecture of highly advanced functional material systems, such as those found in biological systems. The concept of composite nanoarchitectonics is a long way from perfection, but there have been several reports that provide the beginnings of the concept. This review illustrates the reported nanoarchitectonics research on composites and some related functional composite materials. To show the wide range of applications and potential, recent examples are categorized as (i) catalyst & photocatalyst, (ii) energy, (iii) sensing & environment, (iv) bio & medical, and (v) various other functions and applications. In order to show the various stages of development, the examples are not only state-of-the-art, but also include those that are successful developments of existing research. Finally, a summary of the examples and a brief discussion of future challenges in nanoarchitectonics will be given. Nanoarchitectonics is applicable to all materials and aims to establish the ultimate methodology of materials science.

2 Catalyst & Photocatalyst

Various functions require the fulfilment of several necessary elements. To satisfy these elements, nanoarchitectonics, which is a composite of two different materials, is effective. For example, a catalytic function requires two elements: the ability to promote reactions and the structural selectivity of substrates and products. As one that satisfies such properties, Fujiwara reported on an active catalyst for the production of aromatic hydrocarbons by CO_2 hydrogenation [204]. In this catalyst, a composite catalyst consisting of Fe-Zn oxide and a zeolite, H-ZSM-5, was used. This composite catalyst is very effective for the selective formation of aromatic hydrocarbons. The narrow pore size of the zeolite H-ZSM-5 provides excellent geometry selectivity of the reaction, which was also achieved in the methanol-hydrocarbon reaction of CO_2 hydrogenation. Such catalytic technology will contribute to carbon recycling. This will be a necessary technology to realize a sustainable low-carbon society.

Shimakoshi and co-workers nanoarchitectonized high-performance visible light-driven hybrid catalysts from vitamin B_{12} complexes derived from natural vitamin B_{12}, earth metal ions, and titanium dioxide (Fig. 2) [205]. First, metal ions (Cu^{2+}, Ni^{2+}, Fe^{2+}, Zn^{2+}, Mn^{2+}, Al^{3+}, Mg^{2+}, etc.) were modified on the TiO_2 surface. This resulted in an effective response to visible light. Furthermore, vitamin B_{12} complexes were loaded on the surface. In this way, the nanoarchitectonically modified catalyst can promote visible light-driven reactions without the use of precious rhodium. In particular, B_{12}-Mg^{2+}/TiO_2 showed the highest catalytic activity among the prepared samples. This is because electron transfer to the B_{12} complex occurs efficiently because no electron transfer to the modified magnesium side occurs. It was also shown that useful chemical products, *N*,*N*-diethyl-3-methylbenzeamide and *N*,*N*-diethylformamide, can be prepared in high yield under visible light irradiation. Such performance is useful for fine chemical synthesis using sustainable solar energy.

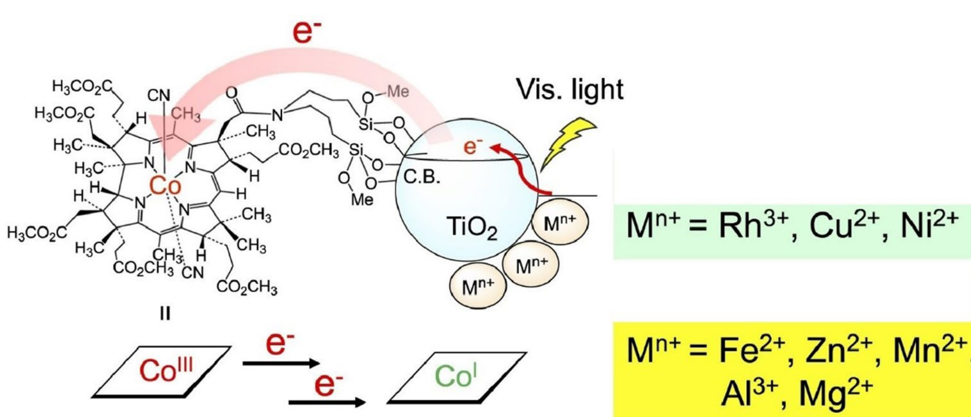

Fig. 2 Hybrid catalysts from vitamin B_{12} complexes derived from natural vitamin B_{12}, earth metal ions, and titanium dioxide that can promote visible light-driven reactions. Reproduced with permission from Ref. [205]. Copyright 2022 Oxford University Press

Hakamy, Abd-Elnaiem, and co-workers reported on nanoarchitectonics of nickel dimethylglyoxime/γ-alumina composites [206]. In this approach, nickel dimethylglyoxime is synthesized on γ-alumina, which is used as a catalyst, using a direct impregnation method. Using this catalyst, the photocatalytic degradation performance for methylene blue and methyl orange was investigated. The photodegradation performance of these dyes was significantly enhanced by compositing, and the Ni microcrystals or Ni nanospheres on the γ-alumina support were analysed as being distributed in a single phase and/or in a homogeneous manner. This support structure enhanced thermal stability and photocatalytic degradation of dyes. In particular, the nanosized form of the γ-alumina catalyst, with its large surface area, is useful for a variety of applications. It may also be suitable for degradation of other dyes. Furthermore, the nanoarchitectonized composite would be suitable for a variety of applications, such as sensing, in addition to catalytic applications.

Abd-Elnaiem et al. reported on graphene oxide-based composite photocatalysts under the concept of composite nanoarchitectonics of graphene oxide [207]. Graphene oxide-bound Au and ZnO nanocomposites were synthesized by a modified Hummers method and an ultrasound-assisted solution method. Photocatalytic degradation of methylene blue was investigated under simulated visible-ultraviolet light irradiation. Porous graphene oxide nanoparticles showed the greatest efficiency and performance in photodegradation. For example, the photocatalytic efficiency for the removal of methylene blue from wastewater reached 97% for the porous graphene oxide nanoparticle catalyst. The best fit for the photocatalytic degradation mechanism was adsorption by an intraparticle diffusion kinetics model. The use of such composite catalysts for the purification of organic dyes is of interest from economic, safety, and environmental perspectives.

3 Energy

Exquisite composite nanoarchitectonics of various components can improve material performance. This methodology has also come in handy for energy-related applications. Li and co-workers have prepared polymer/metal oxide cluster composites based on a site-isolation strategy [208]. This co-polymerization strategy allows the preparation of polymer/inorganic cluster composites with ultrasmall-sized inorganic phases. The maximum probable diameter of the nanoarchitectonized aluminium oxide clusters is 2.2 nm. This technique does not require an auxiliary dispersion step. Nevertheless, the clusters are uniformly dispersed in the polymer matrix. As background, polymer dielectrics need to operate at high temperatures to meet the demands of electrostatic energy storage in modern electronic and electrical systems. Although nanoarchitectonics approaches with polymer nanocomposites have been used to improve performance, they have the drawbacks of reduced energy density and lower discharge efficiency at temperatures above 150 °C. Creating ultra-small inorganic clusters, as in this study, can introduce richer and deeper traps into composite dielectrics compared to conventional polymer/nanoparticle blends. Due to this effect, high-temperature capacitance performance was achieved up to 200 °C. Such composite nanoarchitectonics of polymer/inorganic clusters is useful for high-temperature dielectric energy storage in practical applications of power devices and electronic devices. Combined with the synthetic advantages of inexpensive precursors and one-pot synthesis, this could be a promising method for tuning the high-temperature capacitance performance of polymeric dielectrics.

The development of multifunctional electrode materials is an important approach for practical applications in energy storage and conversion devices. For example, the construction of composite materials based on metal-organic frame work (MOF) is considered a promising strategy. It is important to improve the conductivity of MOF materials through a rational nanoarchitectonics approach. Jiao, Chen, and co-workers have created composites of iron-based MOFs and ultra-thin $Co(OH)_2$ nanosheets by in situ hydrothermal strategies (Fig. 3) [209]. This created a hollow, interconnected porous network structure. Structural and morphological analysis confirms that the $Co(OH)_2$ nanosheets are uniformly anchored on the Fe-based MOF, forming a hollow composite. A large specific surface area with a hierarchical porous structure is provided for electrolyte storage. Therefore, the diffusion of ions is promoted, and the reaction rate of the active material is greatly improved. The hollow structure can expose more active surfaces. The enhanced electrolyte penetration may improve the utilization of iron-based MOFs. The composite materials developed in this study showed excellent performance in both supercapacitors and oxygen evolution reaction. Such nanoarchitectonized composite materials can be used in electrode materials with excellent performance. They also have great potential for development in the field of electrochemistry. It will provide inspiration for future energy storage and conversion device designs.

Wu, Gong, and co-workers have shown how black phosphorus quantum dots can be efficiently used in lithium batteries under the concept of composite nanoarchitectonics for efficient lithium storage [210]. In this study, the goal is to obtain high energy density while improving stability. Black phosphorus quantum dots were co-precipitated into pores matching the size of the cobalt/iron Prussian blue analogues of MOFs. The composite nanoarchitectonics was achieved

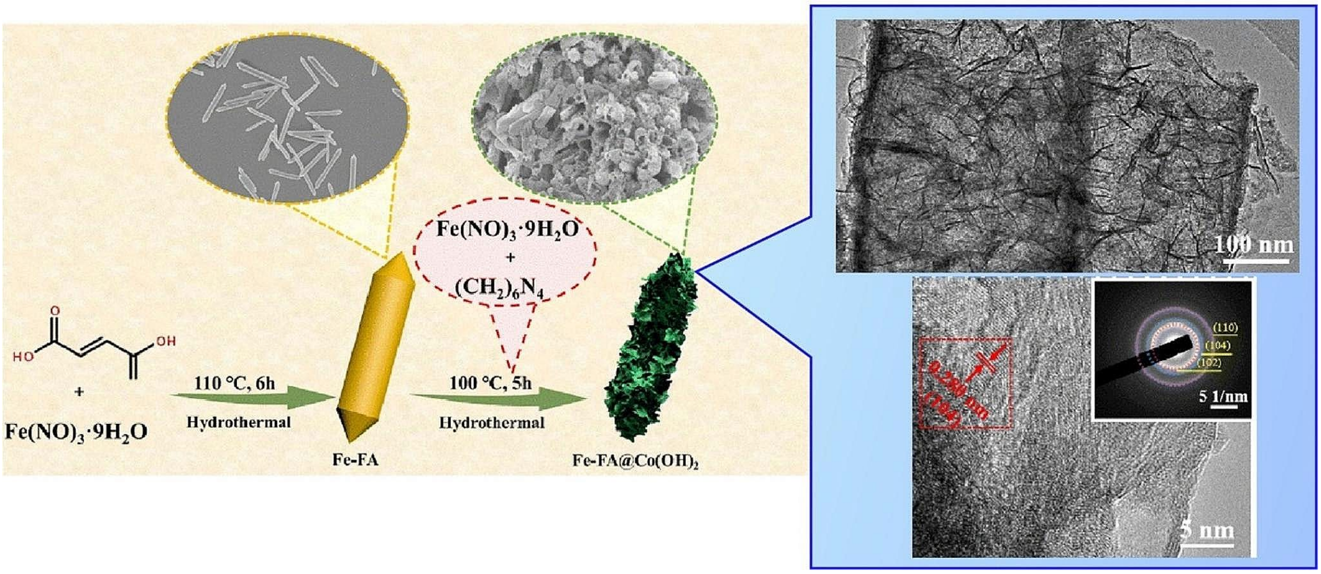

Fig. 3 Composites of iron-based MOFs and ultra-thin $Co(OH)_2$ nanosheets by in situ hydrothermal strategies having a large specific surface area with a hierarchical porous structure for electrolyte storage. Reproduced with permission from Ref. [209]. Copyright 2023 Royal Society of Chemistry

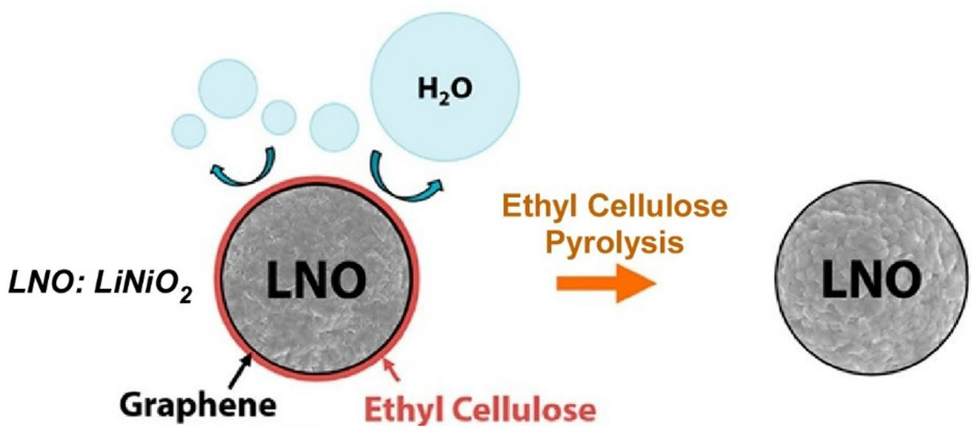

Fig. 4 $LiNiO_2$ (LNO) cathode particles with a uniform coating of a hydrophobic barrier layer composed of graphene and ethylcellulose followed by pyrolysis process. Reproduced with permission from Ref. [211]. Copyright 2023 American Chemical Society

with different amounts of black phosphorus quantum dots encapsulated in the pores of the Co/Fe Prussian blue analogue. The morphology and particle size of the composite were changed without changing the crystal structure of the MOF. The stability of the composite with black phosphorus quantum dots was significantly improved. Excellent electrochemical performance was demonstrated in lithium batteries. The close contact between black phosphorus quantum dots and Co/Fe catalyst sites promoted rapid transfer of lithium ions between metal sites. The lithium storage capacity was also increased due to the special molecular structure of black phosphorus, which forms P-N bonds. The material developed here with black phosphorus quantum dots in Prussian blue analogues encapsulated as electrodes exhibited higher capacity density and longer cycle stability than batteries using conventional Prussian blue analogue composite materials. As a result, this could serve as a guideline for developing lithium batteries with higher capacity density and cycle stability.

Nickel-rich layered oxides are widely used as cathode materials in energy-dense lithium-ion batteries. However, these chemistries, based on the parent compound $LiNiO_2$, are known to be very sensitive to the ambient environment and react readily with moisture and carbon dioxide. This characteristic leads to a significant reduction in performance. To address this issue, Hersam and co-workers prepared $LiNiO_2$ cathode particles with a uniform coating of a hydrophobic barrier layer composed of graphene and ethylcellulose (Fig. 4) [211]. This hydrophobic coating reduced contact between atmospheric moisture and the $LiNiO_2$ surface, minimizing the generation of lithium impurities. The obtained results demonstrate the breaking of the

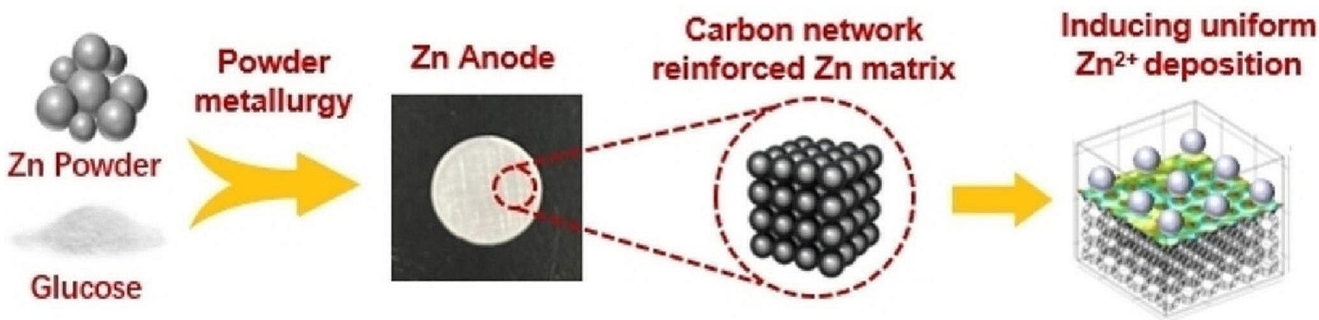

Fig. 5 Fabrication of a Zn matrix composite anode with an implanted 3D carbon network by powder metallurgy with the surface electric field distribution through highly reversible Zn deposition. Reproduced with permission from Ref. [212]. Copyright 2024 Wiley-VCH.

Fig. 6 Process for photoelectric conversion devices; monodisperse MXene quantum dots were obtained by HF etching, exfoliation, and hydrothermal treatment; next, $ZnIn_2S_4$ nanosheet arrays were synthesized on FTO by hydrothermal method; then, MXene quantum dots and α-Fe_2O_3 nanodots were modified on the $ZnIn_2S_4$ nanosheet surface by spin-coating and solvothermal methods. Reproduced with permission from Ref. [213]. Copyright 2024 Wiley-VCH.

Ni-rich limit of the layered lithium transition metal oxide family. This work establishes a scalable strategy for improving the environmental stability of Ni-rich cathode materials. Demonstrating this approach for the ultimate nickel-rich chemistries is likely to be generalizable to a wide range of environmentally sensitive battery materials. In addition, it is expected to be applicable to other related Ni-rich chemistries that are widely used in electric vehicles and related energy storage technologies.

As a promising candidate for grid-scale energy storage, Zn-based aqueous batteries have shown high potentials due to their intrinsic safety, outstanding theoretical energy density, and cost-effectiveness. However, a negative factor against practical application is the performance degradation due to dendrite formation, side reactions, and corrosion of the anode, etc. To address this issue, Zhang, Han, and co-workers have fabricated a new Zn matrix composite anode with an implanted 3D carbon network by powder metallurgy (Fig. 5) [212]. The internal carbon network provides a continuous electron transfer channel. Through optimization of the surface electric field distribution, highly reversible Zn deposition can be achieved. By filling the gaps in the Zn powder, poor connections due to point contacts between particles can be avoided. Thereby improving the conductivity of the electrode. It also provides more nucleation sites for Zn deposition. As a result, the symmetric cell exhibits tremendous stability. The application of powder metallurgy in this study provides new ideas for the preparation of high-performance and low-cost Zn-based aqueous battery anodes. Potential applications for large-scale practical preparation and renewable energy storage are suggested.

To achieve sufficient photoelectrochemical water splitting performance, it is essential to improve charge separation/transport efficiency. In particular, various interface engineering strategies to mitigate charge recombination are essential. Zhang, Du, Lu, and co-workers demonstrated an effective strategy that can synchronously regulate the simultaneous transfer of electrons and holes in different directions on the photoanodes to improve photoelectrochemical performance [213]. Figure 6 shows that monodisperse MXene quantum dots were obtained by HF etching, exfoliation, and hydrothermal treatment. Next, $ZnIn_2S_4$ nanosheet arrays were synthesized on FTO by hydrothermal method. Then, MXene quantum dots and α-Fe_2O_3 nanodots were modified on the $ZnIn_2S_4$ nanosheet surface by spin-coating and solvothermal methods to obtain photoelectric conversion devices. The resulting photoelectric conversion device photoanodes have a synergistic combination of α-Fe_2O_3 nanodots and MXene quantum dots on ZnIn2S4 nanosheets. It has a high photocurrent density and exhibits benchmark photoelectrochemical performance. The above results are mainly due to the MXene quantum dot capturing and storing electrons from the conduction band of $ZnIn_2S_4$, mitigating electron-hole pair recombination and S-O interfacial chemical bonds introduced at the interface between $ZnIn_2S_4$ and α-Fe_2O_3 nanodot efficiently promote carrier transfer. These factors are believed to have led to the photoelectrochemical performance. These interfacial nanoarchitectonics strategies will provide insights for precisely regulating carrier separation and migration. They will provide a better understanding of interfacial charge separation and provide valuable guidance for the rational design and fabrication of high-performance composite electrode materials.

4 Sensing & Environment

There are many social demands in dealing with environmental problems, such as sensing hazardous substances [214–218], removing pollutants [219–223], etc. The targets are diverse. Materials nanoarchitectonics with multi-component components is therefore important for environmental applications. For example, Supreet, Pal, and co-workers have developed a highly responsive and selective methanol gas sensor at room temperature under the concept of composite nanoarchitectonics with reduced-graphene oxide and polyaniline [224]. The approach is based on camphor sulfide. As an approach, reduced-graphene oxide-polyaniline nanocomposites were synthesized by a simple chemical oxidation synthesis process in the presence of camphor sulfonic acid. The morphology of the prepared material was observed to be nanoparticles and semi-crystalline in structure. This gas sensor based on polyaniline doped with reduced graphene oxide showed selective high response to methanol vapor. Specifically, the highest response was found at 200 ppm. Furthermore, the sensor showed excellent stability of more than 85% even after 180 days of fabrication. This cost-effective, responsive, stable, reproducible, and repeatable method may be a good candidate for commercial production of methanol vapor sensors.

Detection of toxic ion species is an important issue for environmental science. Various composite nanoarchitectonics can be used to construct sensors for hazardous metal ions. AL-Refai et al. prepared nanocomposites for sensor electrodes under the concept of composite nanoarchitectonics with polythiophene, carbon nanotubes, CuO and chitosan using an in situ polymer oxidation [225]. The nanocomposites for sensor electrodes were prepared using the in situ polymer oxidation pathway. Specifically, glassy carbon electrodes modified with polythiophene/multiwalled carbon nanotubes, chitosan, and CuO were prepared. The modified electrode prepared exhibited a certain range of detection linearity and excessively yielding ion detection at low concentrations. The high Cd(II) detection efficiency of the sensor with this modified glassy carbon electrode can be regarded as a good success story for electrochemical sensor applications.

Photocatalytic reduction of Hg^{2+} under visible light is an important challenge. This can be improved in performance by a composite nanoarchitectonics approach. Alotaibi, under the approach of composite nanoarchitectonics of PtO decorated mesoporous ZrO_2, has synthesized mesoporous ZrO_2 and PtO by a wet chemical method [226]. The PtO@ZrO2 photocatalyst exhibited high photocatalytic reduction capacity of Hg^{2+} ions. Characteristically, the addition of PtO enhanced the photoactivity of ZrO_2 for Hg^{2+} removal upon visible light irradiation. Factors such as the reduced band gap of PtO@ZrO_2 photocatalyst, broadening of the visible light absorption spectrum, and suppression of charge recombination resulted in superior photoactivity. 1.5% of PtO added to ZrO2 resulted in complete photoreduction of Hg^{2+} within 1 h after visible light irradiation. The newly developed PtO@ZrO_2 photocatalyst in composite nanoarchitectonics has the potential to be used as an environmentally friendly photocatalyst for a variety of environmental transformation phenomena. Moreover, its excellent stability, permanence, and ability to be used in a wide variety of applications make it a potential candidate for industrial applications.

Approaches to remove pollutants and their models from the environment are traditional research, but recognition of their importance remains. Shah and Naglah have developed a powerful material for the removal of dye molecules under the approach of nanoarchitectonics of chitosan/glutaraldehyde/ZnO [227]. In this study, chitosan was cross-linked with glutaraldehyde in the presence of zinc oxide nanoparticles. As a result, a novel composite of chitosan/glutaraldehyde/zinc oxide was obtained. The nanoarchitectonized composite showed efficient removal ability of eriochrome black T dye from aqueous media. The analysis revealed that the adsorption process of eriochrome black T dye is endothermic and spontaneous. It is expected that this complex can be used not only for this dye but also for the removal of various organic and inorganic contaminants.

Photothermal membrane distillation is a promising and sustainable approach for desalination and wastewater purification. Wang and co-workers have developed a hydrogel composite membrane with improved photothermal conversion capacity as well as the fouling and moisture resistance required for photothermal membrane distillation (Fig. 7) [228]. The composite membrane exhibits a synergistic effect of $Ti_3C_2T_x$ MXene nanosheets with photothermal conversion capacity and the tannic acid-Fe^{3+} network in the hydrogel. As a result, the film exhibits excellent surface self-heating capability. The hydrogel composite membrane has high water vapor flux and high solar efficiency under solar irradiation. It is also resistant to oil fouling and surfactant wetting. It can significantly extend the lifetime of membranes in the treatment of contaminated salt water. When desalinated with actual seawater, the membrane exhibited stable vapor flux for 100 h, excellent ion rejection, and superior durability. The lifetime of the membranes in treating contaminated salt water could be significantly extended. The developed photothermal distillation membrane has great potential for the production of standard-compliant water.

5 Bio & Medical

The targets of biochemistry and biomedical applications are complex in many cases. Organisms express their functions by processing complex interactions in an integrated manner. The materials that can deal with them must also have a certain level of complexity. Therefore, various composite nanoarchitectonics will be a force to be reckoned with in this field.

For example, antimicrobial function is a matter of universal importance in the biomedical field. Bahramian and co-workers have raised the concept of nanoarchitectonics of octahedral Co_3O_4/chitosan composite and investigated the photocatalytic activity and antimicrobial properties of cobalt complexes and chitosan [229]. The photocatalytic activity and antimicrobial properties of the cobalt complex and chitosan composite were investigated. Spinel cobalt oxide particles with octahedral shape were synthesized by pyrolysis of cobalt(III) complex precursors. This synthesis does not involve the use of harmful solvents, surfactants, or complicated apparatus. Furthermore, the octahedral-shaped spinel cobalt oxide particles were fixed on a chitosan polymer to form a composite. The performance of this composite in the photolysis of methylene blue was evaluated. It was found that the regular morphology of octahedral-shaped cobalt spinel oxide particles, appropriate band gap energy, and absorption properties of chitosan are necessary for the enhanced photocatalytic activity of the composite. Furthermore, the antibacterial efficiency against two bacteria (E. coli and Staphylococcus aureus) was tested using an agar well diffusion assay. The antimicrobial screening results showed that coating the chitosan polymer with octahedral-shaped spinel cobalt oxide particles enhanced its inhibitory activity against both Gram-positive and Gram-negative bacteria.

Hydroxyapatite-based nanocomposites have potential for various biological applications. El-Naggar et al. examined nanocomposites of these three components under the title nanoarchitectonics of hydroxyapatite/molybdenum trioxide/graphene oxide composite [230]. Electron microscopic analysis and the roughness characteristics observed suggest that utilizing the type and amount of additives to the hydroxyapatite component is a highly effective tactic to tailor a composite suitable for biomedical applications. The optimized triple complex exhibited the highest cell viability against E. coli and Staphylococcus aureus compared to the other compositions.

Antibiotic-resistant bacteria are one of the most dangerous factors causing human disease and endangering public health and social security. One means of controlling this

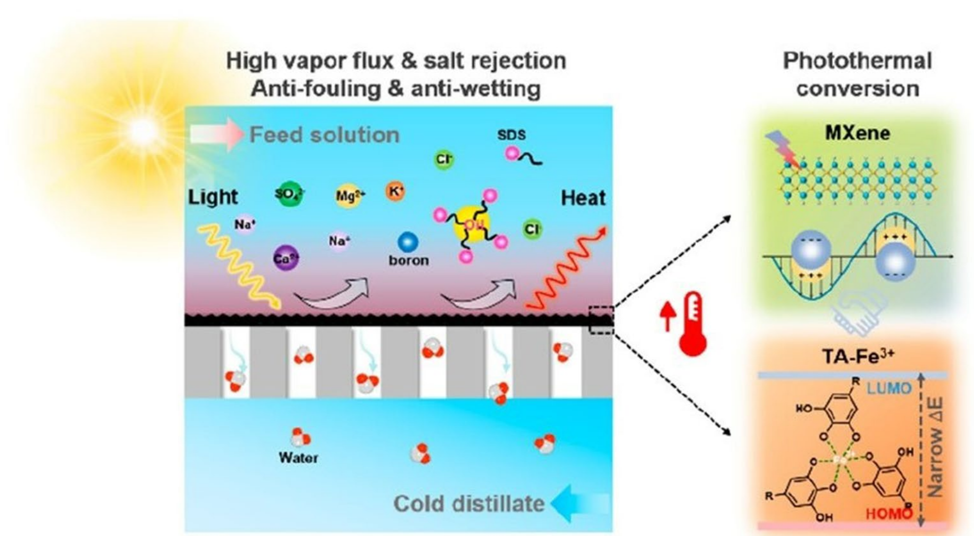

Fig. 7 A hydrogel composite membrane with improved photothermal conversion capacity as well as the fouling and moisture resistance required for photothermal membrane distillation with a synergistic effect of Ti_3C_2Tx MXene nanosheets with photothermal conversion capacity and the tannic acid-Fe^{3+} network in the hydrogel. Reproduced with permission from Ref. [228]. Copyright 2024 American Chemical Society

problem is the use of porous cellulose and other materials to inhibit bacterial membranes and metabolism. This methodology can also be a sustainable strategy for treating bacteria-contaminated water. Under the strategy composite nanoarchitectonics of cellulose with porphyrin-Zn, Chen and co-workers have developed a simple, reusable, and environmentally friendly material for antimicrobial and adsorption applications [231]. They has developed porous, light-responsive fibers to develop a simple, reusable, and environmentally friendly material for antimicrobial and adsorption applications. Specifically, photoresponsive fibers were synthesized from covalently bonded composites of porous cellulose and porphyrin derivatives (Fig. 8). The composite exhibited excellent inhibition and adsorption against both Escherichia coli and Staphylococcus aureus. It showed excellent inhibition against both Gram-negative and Gram-positive bacteria. It was suggested that the bacterial membrane is disrupted via porphyrin-zinc nanospheres. The porous rod-like structural fibers are expected to be applicable for bacterial inhibition and filtration.

Saranya et al. developed composites with anticancer properties using an approach called nanoarchitectonics of cerium oxide/zinc oxide/graphene oxide composites [232]. Using an ultrasonic approach, they developed a material based on cerium oxide/zinc oxide/graphene oxide nanocomposites. The nanocomposites exhibited smoother sheet-like micromorphology. Using antiproliferation assay tests, they evaluated the elimination anticancer ability of these nanosystems against HeLa cell lines at various doses and various culture intervals. Anticancer properties were validated using cytotoxicity, apoptosis, and flow cytometry. The results showed that the newly developed nanocomposites had improved anticancer activity against the HeLa cell line. It also became a better therapeutic agent for cervical cancer.

Spinal cord injury causes permanent loss of sensory and motion function, but effective clinical treatments are needed. In particular, synergistic treatments are urgently needed in clinical practice. Jin, Feng, Wei, and co-workers designed a composite patch for spinal cord injury repair consisting of a nanofiber scaffold and hyaluronic acid hydrogel (Fig. 9) [233]. Compared to traditional invasive treatments, local cellular drug injection, and tissue scaffold implantation, the patch provides a drug-exosome dual release system and may offer a noninvasive method for clinical treatment of spinal cord injury patients. The compound patch suppresses the inflammatory response by polarizing macrophages from M1 to M2 type. And it increases neuronal survival by inhibiting neuronal apoptosis after spinal cord injury. These studies demonstrate the translation of nanoarchitectonics ideas into clinical applications.

Living cells and organisms can be regarded as complex composites composed of numerous biomolecules. They perform complex biological functions by controlling their concentration and spatial distribution in space and time. Against this background, synthetic multi-network hydrogels that mimic extracellular matrices have attracted much attention. Kubota reported their results on supramolecular-polymer composite hydrogels in their recent review article [234]. These gels can be regarded as one of a new class of multi-network hydrogels. These composite hydrogels can

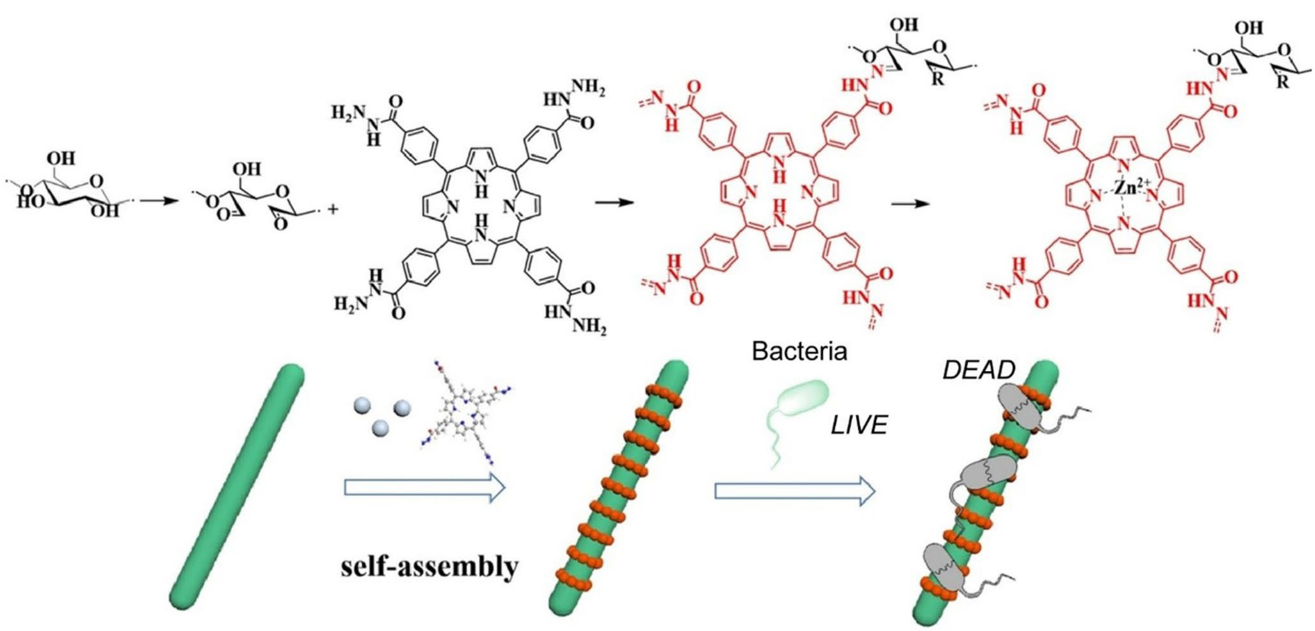

Fig. 8 Photoresponsive fibers synthesized from covalently bonded composites of porous cellulose and porphyrin derivatives for a simple, reusable, and environmentally friendly material for antimicrobial and adsorption applications. Reproduced with permission from Ref. [231]. Copyright 2023 Springer-Nature.

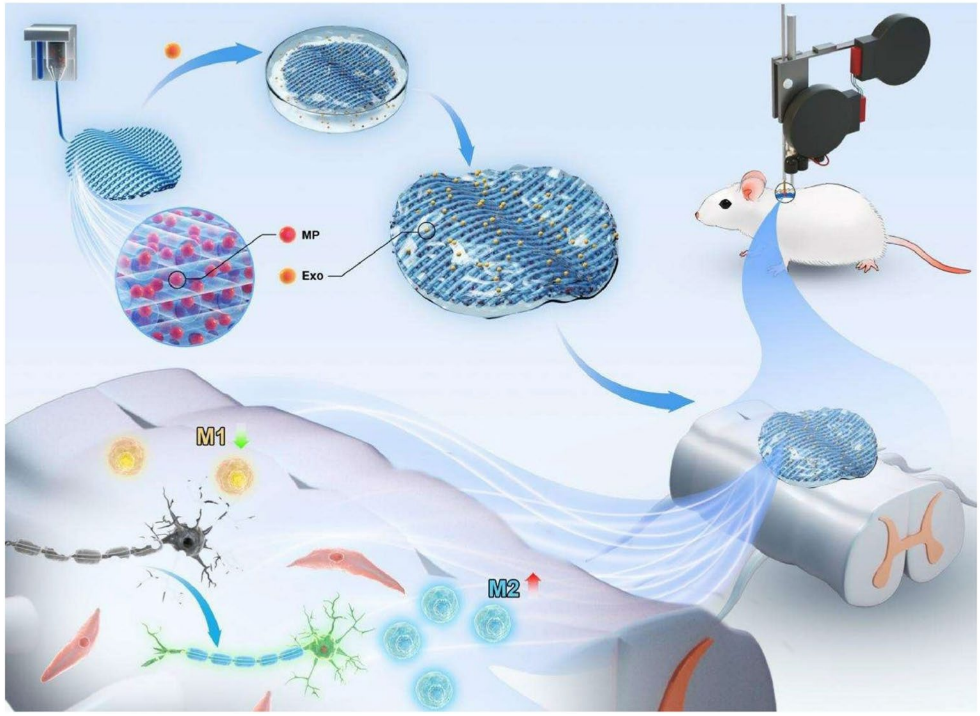

Fig. 9 A composite patch for spinal cord injury repair consisting of a nanofiber scaffold and hyaluronic acid hydrogel. Reproduced with permission from Ref. [233]. Copyright 2023 American Chemical Society

rationally integrate the stimulus response of supramolecular gels with the stiffness of polymer gels. Furthermore, supramolecular-polymer composite hydrogels have potential applications in controlled release of protein biopharmaceuticals. Supramolecular-polymer composite hydrogels can incorporate functional molecules such as enzymes or their inhibitors as a matrix. This allows for the release of protein biopharmaceuticals in response to antibodies. Supramolecular-polymer composite hydrogels are expected to be the next generation of smart and responsive soft materials for biomedical applications including tissue engineering and regenerative medicine. Thus, the spatiotemporally controlled fabrication of functional composite soft materials will produce a variety of functions. This includes biomedical applications such as 3D controlled release of drugs/proteins, construction of hierarchical organoids, and development of implantable/injectable gel devices.

Natural bio-systems skilfully use cascade reactions. Mimicking the processes of this cascade is a highly attractive target. However, orderly assembly of different enzyme-like functions is not always easy. Cheng, Wang, Yin, and co-workers have developed a composite with three-in-one functionality (Fig. 10) [235]. In this composite, a single gold-platinum nanozyme provides oxygen as a mimetic catalase. It also produces H_2O_2 through glucose oxidase-like properties. In addition, it initiates a cascade conversion for ·OH generation as a mimetic peroxidase for chemodynamic therapy. Metastable Cu_2O nanoparticles were used as scaffolds to immobilize ultrasmall Au-Pt nanozymes. MOF was used to encapsulate the nanozymes. Porous MOF shells were constructed in situ to confine and stabilize the Au-Pt nanozymes to enhance their mimetic activity. On top of that, pluronic F127 was modified on the surface to improve the hydrophilicity and biocompatibility of the composite. After internalization by tumour cells, the Cu(II)-MOF shell is degraded by endogenous acidity and glutathione. The nanozymes are exposed for cascade catalytic chemodynamic therapy. Exposed Au-Pt nanozymes interact with intertumoral H_2O_2 to form O_2 via catalase-like activity. H_2O_2 with glucose oxidase-like properties for ·OH formation was generated as a mimetic peroxidase for cascade chemodynamic therapy. Laser irradiation at 808 nm induced local hyperthermia and promoted catalytic activity for ·OH formation. The high photothermal conversion capacity also enhanced chemodynamic therapy, and Cu^{2+} ions consumed glutathione to further improve chemodynamic therapy efficiency as an enhancement of cascade catalytic tumour therapy. Three-in-one nanozyme systems improve the efficacy of tumour therapy and minimize side effects on normal tissue. This is a new paradigm with drug-free single nanoteams.

6 Various Other Functions and Applications

The possibilities of materials assembled by composite nanoarchitectonics are enormous. The range of applications is also diverse. From basic research to applications can be found. The following are examples of some of these studies in various fields.

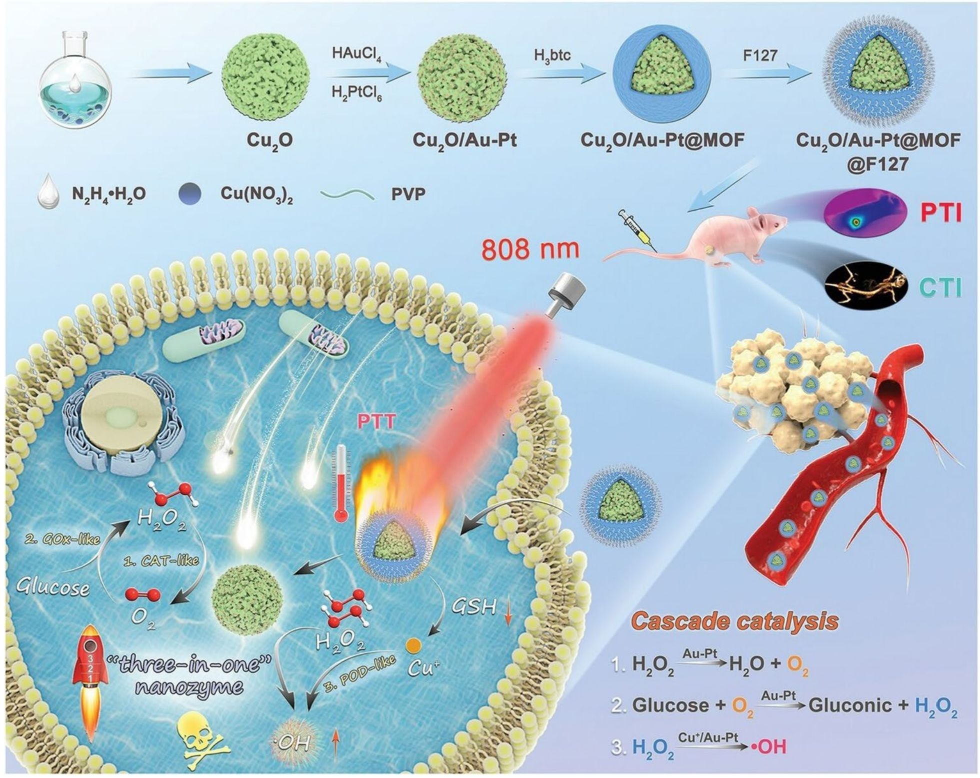

Fig. 10 A composite with three-in-one functionality that improves the efficacy of tumour therapy and minimize side effects on normal tissue. Reproduced with permission from Ref. [235]. Copyright 2024 Wiley-VCH.

Takaguchi, Orita, and co-workers investigated photo-electron transfer reactions in composites of dyes on carbon nanotubes [236]. Namely, visible light absorbing anthrylene and ferrocenoyl substituted acetylene dyes were composited with single-walled carbon nanotubes. Specifically, copper-catalysed dimerization reactions of anthrylene and ferrocenoyl-substituted terminal ethynes were used. In addition, composite one-pot nanoarchitectonics was achieved by subsequent adsorption of butadiyne dye onto single-walled carbon nanotubes. The dye-nanotube composite was dispersed in water using an amphiphilic poly(amidoamine) dendrimer. In this composite, irradiation with visible light (> 422 nm) allowed the transfer of electrons from 1-benzyl-1,4-dihydronicotinamide to methyl viologen dichloride. This compositing methodology of adsorbing anthrylene and ferrocenoyl will pave the way to novel visible-light organic dyes to photocurrent conversion.

In the concept of micro-nanoarchitectonics of electroless Cu/Ni composite materials based on wood, Pan, Huang, and co-workers fabricated Cu-Ni multilayer composites by a simple electroless Cu and Ni method on wood surfaces [237]. As materials based on wood, Cu-Ni multilayer composites were fabricated by a simple electroless Cu and Ni method on wood surfaces. Wood was composited by two times electroless Cu and one time electroless Ni to obtain an ideal surface roughness profile. The metallic Cu and Ni were embedded closely together on the surface of the wood, forming a dense composite layer. The three Ni/Cu Cu/Cu Cu/Wood layers with different electro-magnetic properties induced multiple reflections at their interfaces. This promoted absorption attenuation and enhanced the electromagnetic shielding effect. It was verified that this multilayer composite material can block more than 99.99% of incident electromagnetic waves.

Lightweight structural materials with various combinations of high stiffness, high strength, high toughness, and high hardness have a wide range of uses. Although the development of such materials is highly desired, they are not always easy to fabricate artificially. On the other hand, some biological structural materials have hierarchically heterogeneous structures bounded by gradient interfaces. Structures ingeniously integrate multiple mutually exclusive mechanical properties. Gao, Yu, and co-workers proposed a simple bottom-up approach to fabricate such materials by combining continuous nanofiber-assisted evaporation-induced self-assembly, stacking, pressure-free sintering, and resin infiltration method (Fig. 11) [238]. They have produced a large scale ceramic-resin composite inspired by pearls with a tunable heterogeneous structure. This ceramic-resin composite has a tough, pearl-like body and a rigid, hard outer surface. A gradient intermediate layer was introduced between these two parts to provide a gradual transition between adjacent dissimilar layers. This effectively mitigated the mismatch of properties between the different layers. As a result, mutually exclusive mechanical properties were successfully integrated into a single material. The

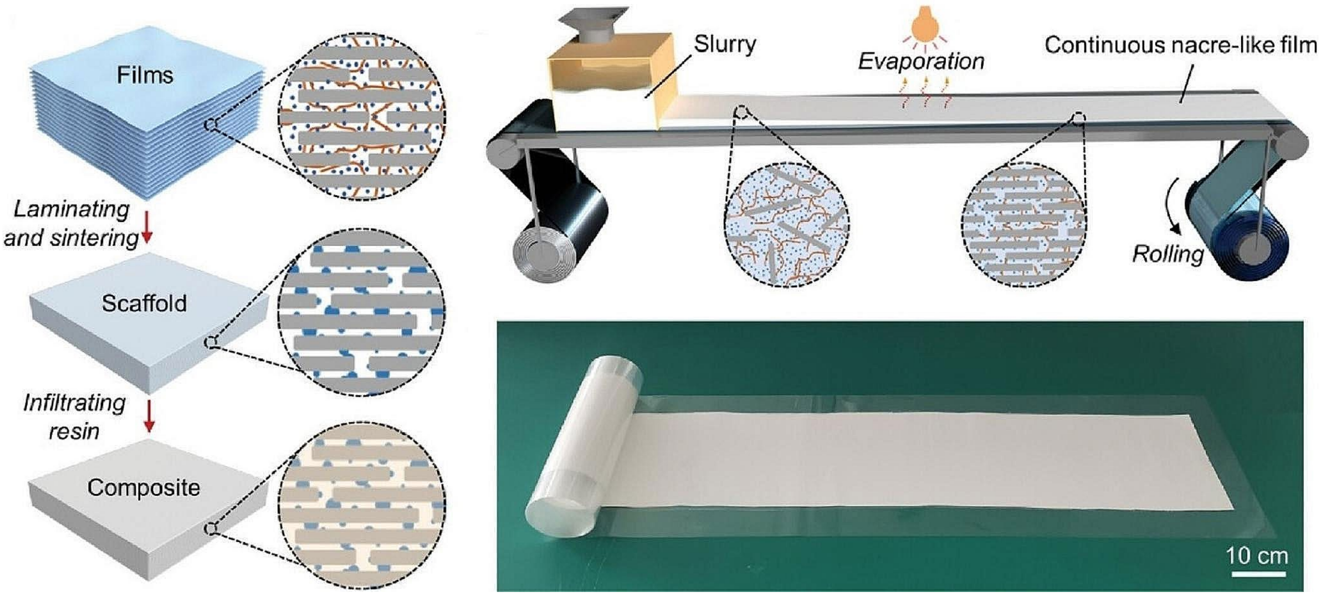

Fig. 11 A simple bottom-up approach to fabricate lightweight structural materials with high stiffness, high strength, high toughness, and high hardness by combining continuous nanofiber-assisted evaporation-induced self-assembly, stacking, pressure-free sintering, and resin infiltration method. Reproduced with permission from Ref. [238]. Copyright 2023 Wiley-VCH.

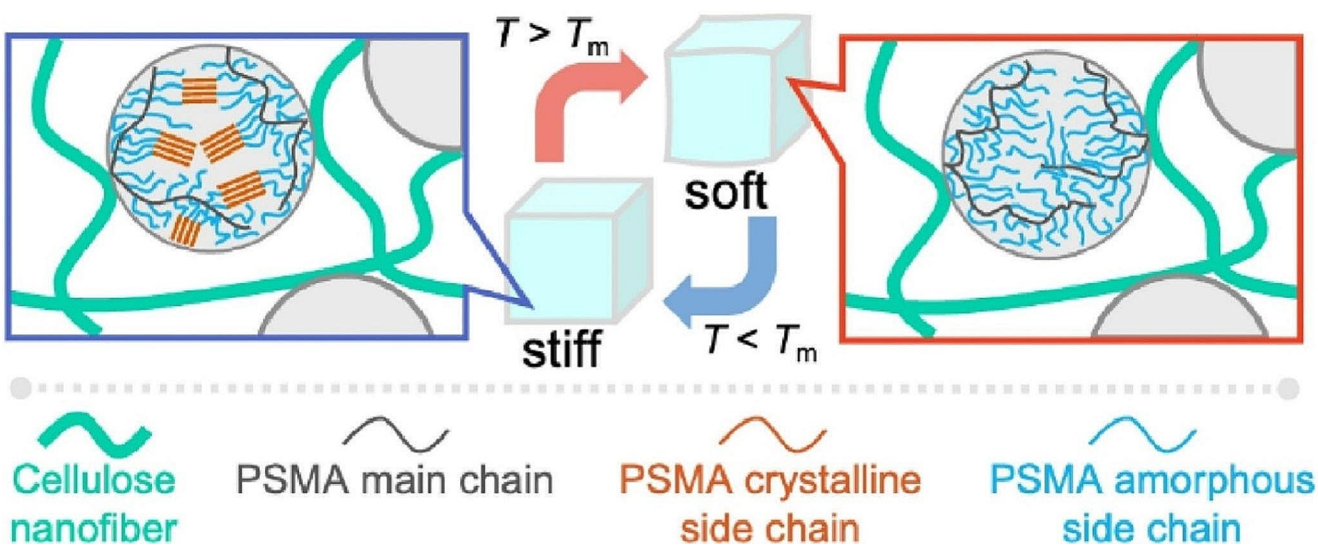

Fig. 12 A hydrogel that can switch mechanical strength depending on temperature by incorporating poly(stearyl methacrylate) as a response domain in bacterial cellulose as a support hydrogel. Reproduced with permission from Ref. [239]. Copyright 2023 Oxford University Press

methodology presented here paves the way for the design of advanced bio-inspired heterogeneous materials for diverse structural and functional applications. It is expected that advanced materials with diverse functions, not only structural, will be designed and manufactured on an industrial scale.

Uyama and co-workers developed a hydrogel that can switch mechanical strength depending on temperature by incorporating poly(stearyl methacrylate) as a response domain in bacterial cellulose as a support hydrogel (Fig. 12) [239]. Poly(stearyl methacrylate) particles in bacterial cellulose showed a reinforcing effect below their melting temperature and a decreasing effect above the melting temperature. This remarkable temperature response behaviour occurs because poly(stearyl methacrylate) particles act as an effective reinforcing filler in the material in the hard state and have little effect on the mechanical strength of the support network in the soft state. The responsiveness of the composite gel can be adjusted simply by varying the amount of poly(stearyl methacrylate). Increasing the amount of incorporated poly(stearyl methacrylate) particles widened the difference between the hard and soft states of the composite. The development of such strength-responsive materials will facilitate the industrial utility of hydrogels as artificial muscles and soft robotic components.

Hydrogel materials show promise for use in a variety of fields, including flexible electronic devices, bio-tissue engineering, and wound dressings. Gao and co-workers have developed hydrogels with the synergistic effects of hydrogen bonding, metal coordination bonding, and electrostatic interactions (Fig. 13) [240]. Based on these multiple synergistic effects, composite hydrogels have high mechanical strength, rapid self-healing, and efficient self-healing capabilities. The hydrogels were prepared by a simple one-pot method. A homogeneous prepolymer solution containing branched polyethyleneimine, acrylic acid, glycerol, zirconyl chloride octahydrate, photoinitiator, and water was dispersed in a glass container and polymerization was initiated by UV irradiation. Because of the multiple reversible effects at work, hydrogels have excellent self-healing capabilities. For example, a disrupted hydrogel achieved 95% self-healing within 4 h at room temperature. Composite hydrogels had programmable and reversible shape transformation properties. It also exhibited outstanding fatigue resistance properties. The introduction of glycerol gave the hydrogel excellent antifreeze and moisture retention properties. These multifaceted high functionalities are expected to contribute to the smart materials industry.

Kobayashi and co-workers prepared Eu(III) composite materials from europium compounds and tetramethylammonium acetate using a solvent-free mechanochemical process [241]. The composite material was found to have a bimetallic structure that functions as a bridge molecule between multiple Eu(III) complexes. The composite exhibits its outstanding photoluminescence performance and excellent circular polarization activity. It also exhibits thermal stability. Due to the convenience, efficiency, and sustainability of green chemistry, the solvent-free nanoarchitectonics of luminescent lanthanide materials is highly promising.

Miyazaki and Yamada prepared praseodymium oxide particle-embedded composite films using praseodymium nitrate and urethane resin as starting materials [242]. By irradiating the prepared composite films with ultraviolet light, composite films containing Pr_6O_{11} nanoparticles of various particle sizes can be obtained. This does not require a heating process at high temperatures, as is common in the preparation of praseodymium-doped glass, as UV irradiation can form praseodymium oxide nanoparticles in the composite films. The resulting composite film exhibited a

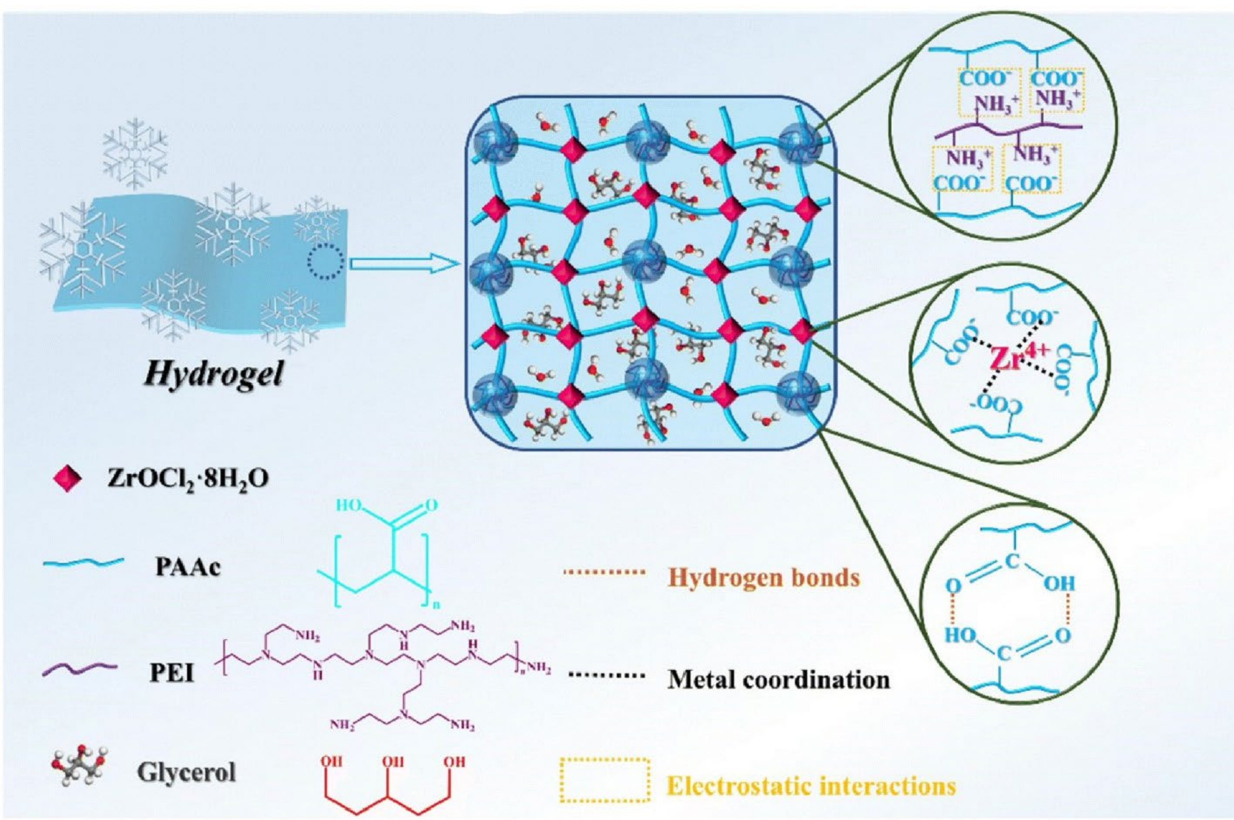

Fig. 13 Hydrogels with the synergistic effects of hydrogen bonding, metal coordination bonding, and electrostatic interactions. Reproduced with permission from Ref. [240]. Copyright 2023 Royal Society of Chemistry

PL property at 605 nm when excited at 444 nm, corresponding to the photoluminescence of the $^1D_2$->$^3H_4$ transition of Pr^{3+}.

Electrochromic devices have a variety of applications, including energy-saving devices and displays. Under the policy of facile nanoarchitectonics of electrochromic devices, Kim, You, and co-workers have created electrochromic devices using transparent bioplastic composite substrates (Fig. 14) [243]. Specifically, novel electrochromic devices based on poly(3,4-ethylenedioxythiophene) (PEDOT)/2,2,6,6-tetramethylpiperidine-1-oxide cellulose nanofiber (TEMPO-CNF)/epoxy composite materials were fabricated by simple solution nanoarchitectonics by simple solution cast polymerization. The PEDOT layer (PEDOT/TEMPO-CNF/epoxy) coated on the TEMPO-CNF/epoxy substrate functions as a conductive electrode. It showed a reversible colour change between light blue (translucent state) and dark blue (coloured state) depending on the redox potential. In other words, a reversible colour switch between light blue and dark blue could be caused. Such a composite nanoarchitectonics approach could be a simple fabrication route for various energy-saving smart windows and high-contrast displays.

Effective waterproofing or encapsulation systems are essential for reliable and durable operation of electronic devices, etc. Hwang and co-workers have developed a stretchable, bioabsorbable encapsulants (Fig. 15) [244]. The composite has a stretchable biodegradable array of pillars composed of a biodegradable elastomer, poly(l-lactide-co-ε-caprolactone), and biocompatible/biodegradable nanoparticles, polytetrafluoroethylene and silicon dioxide. The micro-pattern reduces the diffusion area of water molecules. The embedded nanoparticles block water permeation, which synergistically enhances the water barrier performance. In the initial stage of exposure to water, the surface repelled the wetting of water droplets. Subsequently, the nanoparticles embedded in the polymer matrix physically inhibited water penetration. These synergistic effects lengthen the timescale for water molecules to reach the electronics. The composite for stretchable bioabsorbable electronics acts as a base encapsulating film. It will be able to ensure stable device functionality over a long period of time.

The development of polydimethylsiloxane elastomers with high self-healing efficiency and excellent mechanical properties is a very attractive research target. Zhang, He, and co-workers have created composite elastomers based on polydimethylsiloxane with ultrafast light-controlled healing capability and toughness (Fig. 16) [245]. The dynamic bond breakdown and reconstruction and the strengthening effect of the carbon nanotubes contained in the composite elastomer are observed. Therefore, the composite elastomer exhibited excellent fracture toughness derived from good yield strength and elongation. Furthermore, with the help of dynamic polymer/filler interfacial interactions, carbon nanotubes can quickly and directly heat the damaged part of the composite and achieve ultra-fast repair. As a result, the

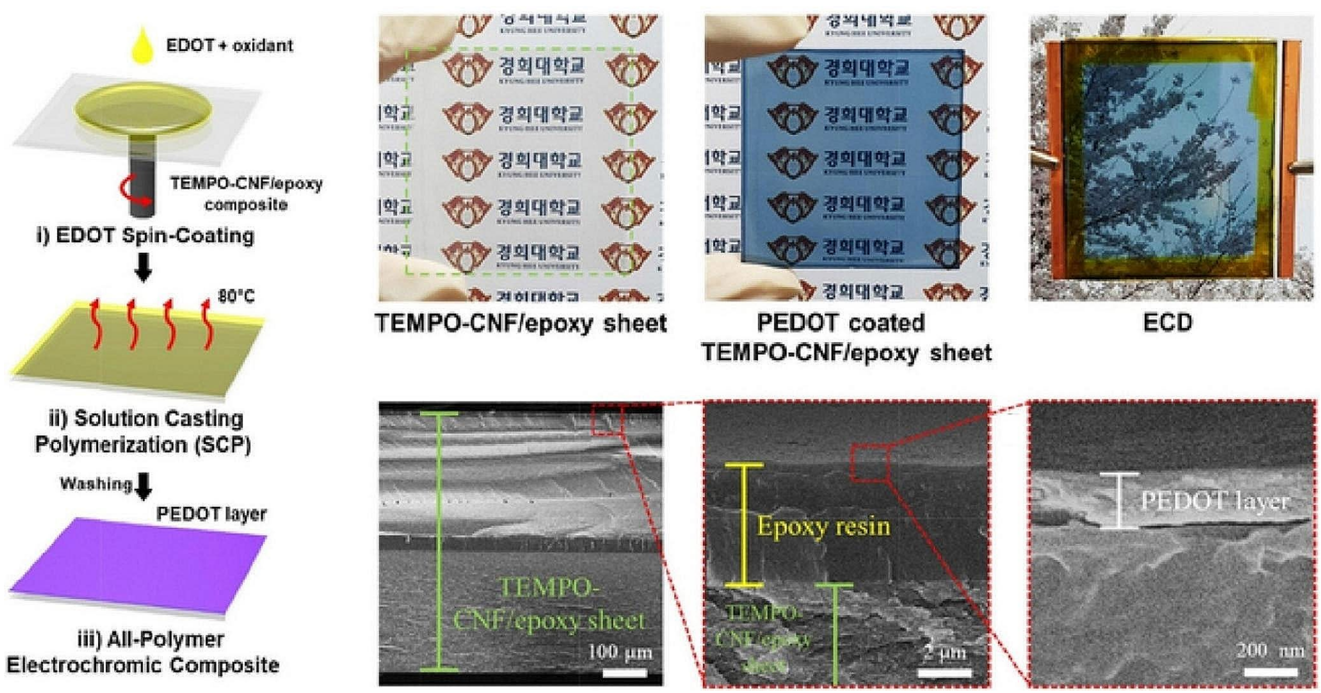

Fig. 14 Electrochromic devices using transparent bioplastic composite substrates based on poly(3,4-ethylenedioxythiophene) (PEDOT)/2,2,6,6-tetramethylpiperidine-1-oxide cellulose nanofiber (TEMPO-CNF)/epoxy composite materials fabricated by simple solution nanoarchitectonics by simple solution cast polymerization. Reproduced with permission from Ref. [243]. Copyright 2023 Elsevier

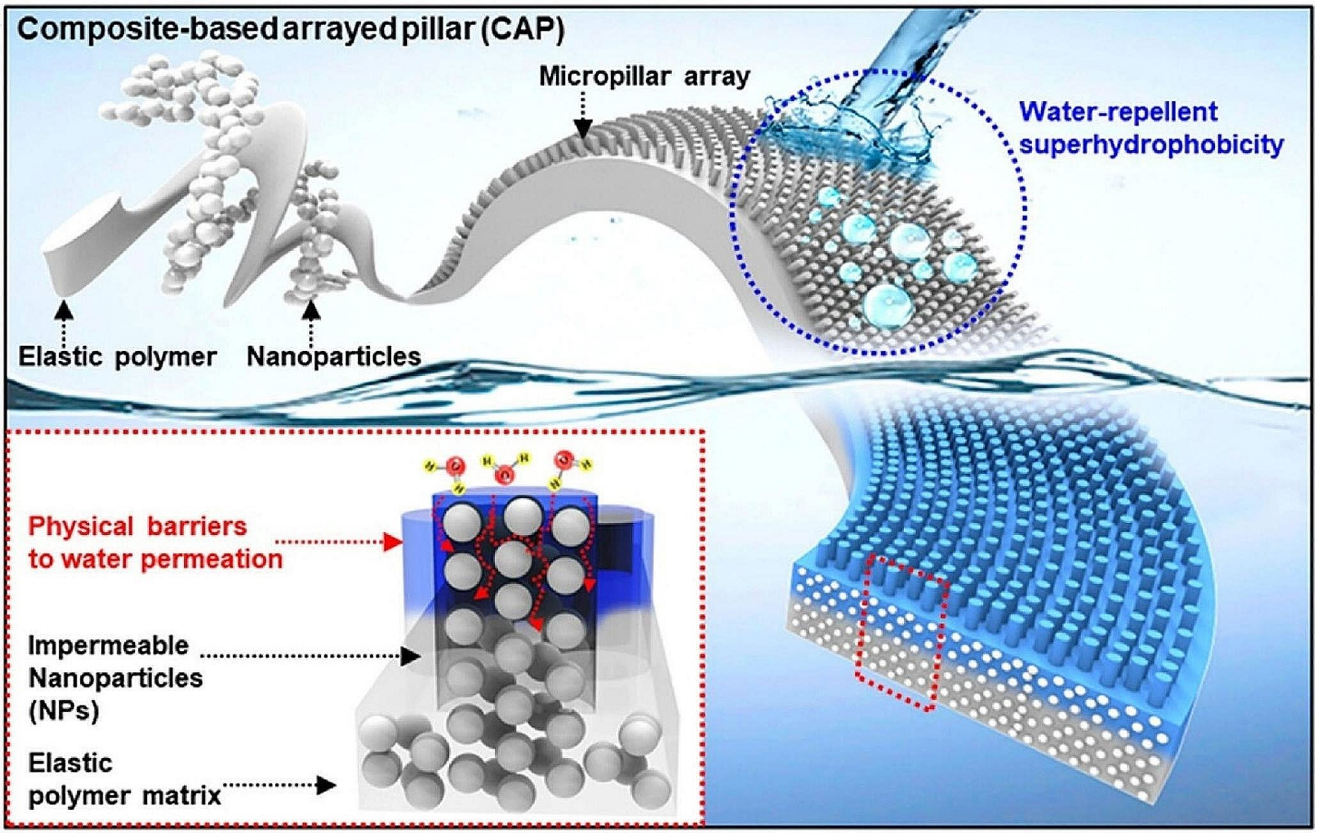

Fig. 15 Composite with a stretchable biodegradable array of pillars composed of a biodegradable elastomer, poly(l-lactide-co-ε-caprolactone), and biocompatible/biodegradable nanoparticles, polytetrafluoroethylene and silicon dioxide in which the micro-pattern reduces the diffusion area of water molecules, and the embedded nanoparticles block water permeation, which synergistically enhances the water barrier performance. Reproduced with permission from Ref. [244]. Copyright 2023 American Chemical Society

self-repair time is significantly reduced. In other words, this dual reversible network nanoarchitectonics strategy successfully reconciles the conflicting properties of mechanical performance and self-healing efficiency. Such materials can be expected to have ultra-fast self-healing efficiency, capable of completing the self-repair process in a few minutes. The materials will have excellent toughness and self-healing brains. It will encourage a variety of further practical applications, such as remote freeze/thaw materials. The composite elastomer has potential applications as a remote de-icing surface.

Daytime passive radiative cooling is a promising methodology for reducing energy demand and mitigating global warming. However, surface contamination due to dust and bacteria deposition hinders practical passive radiative cooling applications. Cai and co-workers proposed composite nanoarchitectonics to integrate passive radiative cooling materials with self-cleaning and antimicrobial functions [246]. Hierarchically patterned nanoporous composite materials were developed using a simple template molding method (Fig. 17). Radiative cooling and superhydrophobic properties can be achieved by creating hierarchical structures at different length scales. The majority of the film is made of a polymer matrix and nanoparticle filler. The pore size of the polymer matrix is designed to be comparable to the wavelength of sunlight (400–2000 nm). Sunlight is strongly scattered at the interface between the surface and the interior according to the difference in refractive index. Nanoparticle fillers are added to adjust the infrared radiation properties of the film; ZnO nanoparticles allow for infrared transparency. SiO_2 particles also increase the IR emissivity. Air fills the tiny valleys on the film surface, which reduces solid-liquid adhesion and makes the film superhydrophobic. This design and manufacturing approach will aid in the long-term operation of passive radiative cooling applications because of its simplicity and versatility.

Wang and coworkers have developed composite materials with good electromagnetic wave absorption properties by Nanoarchitectonics of SiC/multilayer graphene composite powders [247]. Specifically, SiC/multilayer graphene composite powders were synthesized by a simple catalyst-assisted carbon thermal reduction method using silicon dioxide and expanded graphite. Graphene has a unique internal microstructure, high dielectric loss, and

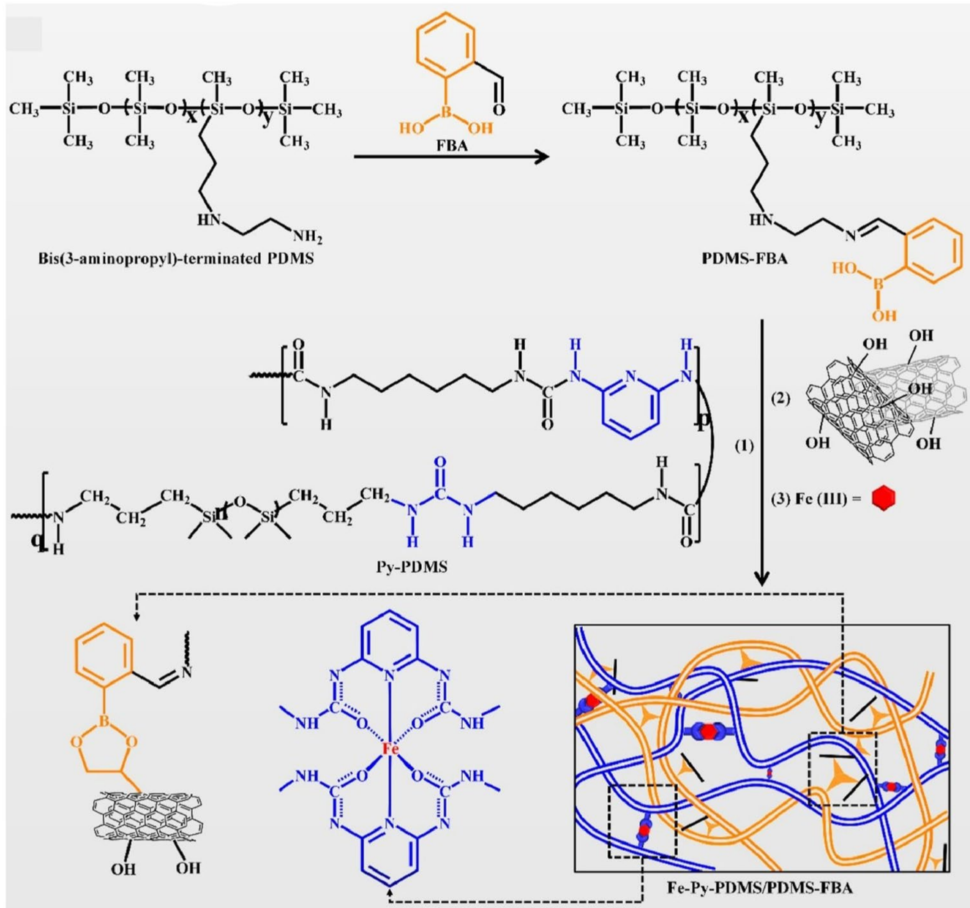

Fig. 16 Composite elastomers based on polydimethylsiloxane with ultrafast light-controlled healing capability and toughness with dynamic bond breakdown and reconstruction and the strengthening effect of the carbon nanotubes contained in the composite elastomer. Reproduced with permission from Ref. [245]. Copyright 2023 American Chemical Society

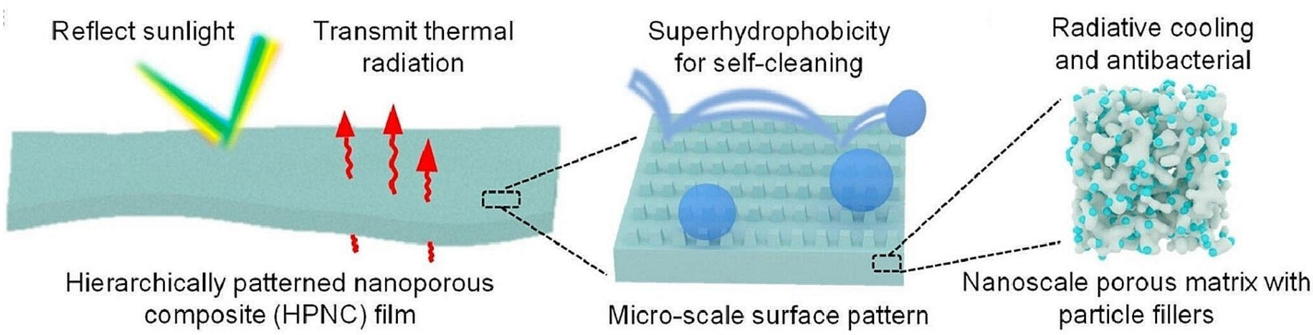

Fig. 17 Composite nanoarchitectonics to integrate passive radiative cooling materials with self-cleaning and antimicrobial functions with radiative cooling and superhydrophobic properties. Reproduced with permission from Ref. [246]. Copyright 2023 American Chemical Society

good electrical conductivity, which improves the impedance matching of the material and increases magnetic loss. the SiC/multilayer graphene composite powder could be an excellent electromagnetic wave absorber. In-situ synthesis of graphene is an effective way to improve the electromagnetic wave absorption properties of SiC nanopowders. With an appropriate excess amount of expanded graphite, multilayer graphene of appropriate thickness is formed in-situ in the composite powder. The structure-optimized composite exhibits optimal electromagnetic wave absorption properties. The three-dimensional dispersion nanoarchitectonics of graphene improves the impedance matching of the material. The advantages of large specific surface area, high defect density, and excellent electrical conductivity increase dielectric and magnetic losses.

Wood-based solar steam generators are gaining prominence in the field of desalination and water purification. The material is considered to be particularly cost-effective and renewable. Li, Xu, and co-workers have developed a unique bilayer composite that incorporates polyaniline nanorods homogeneously into a 3D mesoporous matrix of natural wood (Fig. 18) [248]. The synthesis is a simple, efficient, and environmentally friendly one-step approach. Wood decorated with polyaniline exhibited ultra-high absorbance over a wide wavelength range due to the conjugation of wood with coral-like polyaniline nanorods. In particular, the large number of aligned wood microchannels allowed constant and rapid water transport at the air-water interface under the pressure of capillary forces. This effect generates water vapor at a high evaporation rate. The result is a robust, low-cost, promising evaporator that can be used for water purification. Polyaniline wood exhibits long-term floatability and is chemically stable. Therefore, it could be an ideal candidate for low-energy solar-driven water evaporation applications.

Widely used flame retardants have been brominated flame retardants, which are problematic because of their harmful properties. In response to such problems, there is a need to develop environmentally friendly flame retardants. Choy and co-workers have developed a flame retardant composite using a tactic called composite nanoarchitectonics with ionic clay nanofillers-embedded polypropylene [249]. Specifically, polypropylene is used to composite ionic nanofillers, layered double hydroxide (LDH) and cationic clay (mica). The ionic nanofillers are modified with stearate and cetyltrimethylammonium to make them compatible with polypropylene. In other words, to improve the molecular bonding interaction of ionic nanofillers, anionic stearate and cationic cetyltrimethylammonium surfactants were inserted between the clay layers and the corresponding nanofillers were synthesized by coprecipitation and ion exchange reactions. The composite material exhibited excellent flame retardant properties. Well-dispersed anionic and cationic clay nanosheets in the polymer matrix significantly enhance thermal stability, mechanical properties, and flame retardancy. It is expected that a similar methodology can be applied to various polymer composite materials, where a rational composite of anionic and cationic clays can be used to develop environmentally friendly flame retardants with improved thermal and mechanical properties.

Habi and co-workers have developed composite materials for package applications under the design guideline of composite nanoarchitectonics of poly(lactic acid)/metal-organic framework. Specifically, they used poly(lactic acid) (PLA), metal-organic framework (MOF-5), and metal-organic framework/graphene oxide (MOF-5/GO) [250]. The nanocomposites were prepared by melt extrusion using a vertical co-rotating biaxial microcompounder. In particular, the water vapor permeability was strongly reduced by the incorporation of MOF-5/GO. The presence of MOF-5/GO filler was found to have a significant impact on the water vapor barrier properties. This property will be a useful insight for the development of materials with tailored barrier properties in packaging, especially in food packaging.

7 Summary and Perspectives

Nanoarchitectonics is a post-nanotechnology concept that involves building functional materials that reflect the nanostructures. Functional material systems are assembled from units such as atoms and molecules. Since materials are in principle made of atoms and molecules, the methodology of nanoarchitectonics may be applicable to the creation of all materials science. In particular, the approach of combining and building multiple types of components to create

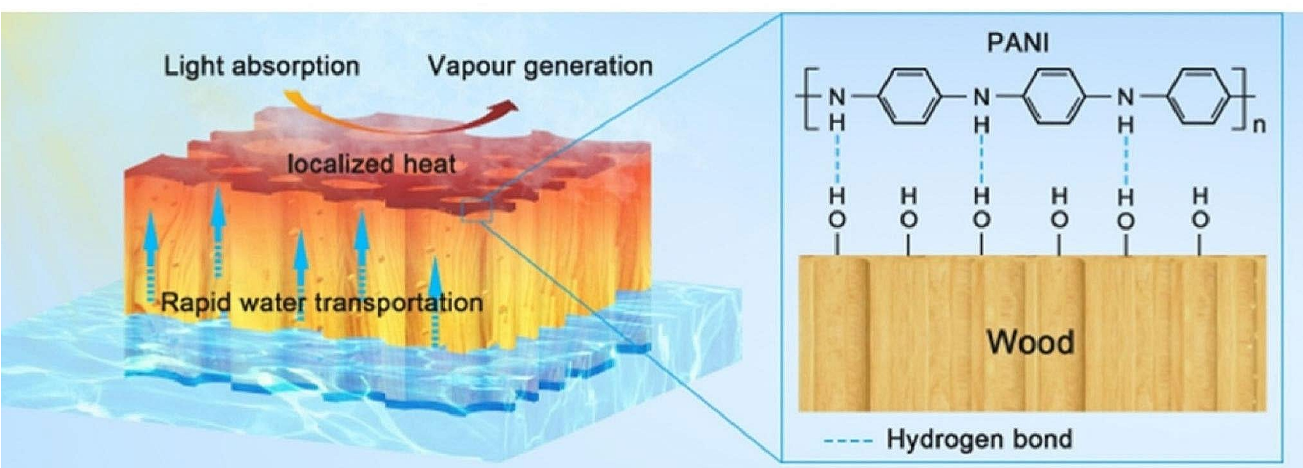

Fig. 18 A unique bilayer composite with incorporates polyaniline nanorods homogeneously into a 3D mesoporous matrix of natural wood in which the large number of aligned wood microchannels allowed constant and rapid water transport at the air-water interface under the pressure of capillary forces. Reproduced with permission from Ref. [248]. Copyright 2023 Oxford University Press

composite materials is an area where nanoarchitectonics can be a powerful tool. In fact, there are many examples of research that have developed composite materials advocating the concept of nanoarchitectonics. This review summarizes such examples and related composite studies. In particular, examples are presented in the areas of catalyst & photocatalyst, energy, sensing & environment, bio & medical, and various other functions and applications to illustrate the potential for a wide range of applications. Although these examples are not all very advanced applications, they demonstrate that composite nanoarchitectonics has the potential for a wide variety of applications. This is due to the versatility of composite materials and the high degree of freedom of nanoarchitectonics. What is also characteristic is that there are a great number of examples where several different properties can be combined and multitasking is possible. This fulfils the direction of building functional material systems with characteristics similar to those of the highly functional systems realized by biological systems.

The possibilities for composite nanoarchitectonics are broad, but several issues need to be addressed for further development. Here, I would like to address two points. The first is that the old approach to architecture of very complex systems will face difficulties. The ideal form of composite nanoarchitectonics is one in which a very large number of functional molecules, such as in biological systems, are rationally organized to perform their functions. Systems that are more complex than a certain degree may not be able to keep up with existing theoretical, deductive, and human empirical functional approaches. However, humans have developed artificial intelligence to process information beyond human capabilities, including concepts such as materials informatics [251–253] and materials development through machine learning [254–256]. It has been widely demonstrated that artificial intelligence can contribute to materials science. It has been also proposed that nanoarchitectonics can be integrated with the concept of materials informatics [257, 258], and the active introduction of artificial intelligence technology will further develop composite nanoarchitectonics with a wide variety of extremely large numbers of components. The active introduction of artificial intelligence technology will further grow composite nanoarchitectonics with a wide variety of diverse and extremely large numbers of components.

Another key solution is coupling with mass production technologies for industrial applications. As demonstrated in several examples in this review, composite nanoarchitectonics has a strong potential to combine several inherently conflicting properties. This is because multi-component or multi-functional units can be rationally architectured in a single functional material system. These features pave the way for practical materials development. It has the ability to transform single-function research examples into practical products that can meet a variety of requirements. To expand such industrial potential, technology for mass production should be developed. This may also require process optimization using artificial intelligence. It would also be very interesting to develop artificial synthesis machines for complex processes through the use of robot technology.

If we can solve the above problems, we may be able to develop a device that automatically prefects very complex material systems. Nanoarchitectonics is a method for everything in materials science. A nanoarchitectonics machine may become the ultimate device to create all materials from atoms and molecules. Humans may create devices that produce functional material systems that function as versatile as living organisms.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

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