

REVIEW

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Advanced nanomaterials for modulating Alzheimer's related amyloid aggregation

Xu Shao,^{ID}†^a Chaoren Yan,^{ID}†^b Chao Wang,^a Chaoli Wang,^c Yue Cao,^e Yang Zhou,^d Ping Guan,^{*a} Xiaoling Hu,^{*a} Wenlei Zhu^{ID}*^e and Shichao Ding^{ID}*^f

Alzheimer's disease (AD) is a common neurodegenerative disease that brings about enormous economic pressure to families and society. Inhibiting abnormal aggregation of A β and accelerating the dissociation of aggregates is treated as an effective method to prevent and treat AD. Recently, nanomaterials have been applied in AD treatment due to their excellent physicochemical properties and drug activity. As a drug delivery platform or inhibitor, various excellent nanomaterials have exhibited potential in inhibiting A β fibrillation, disaggregating, and clearing mature amyloid plaques by enhancing the performance of drugs. This review comprehensively summarizes the advantages and disadvantages of nanomaterials in modulating amyloid aggregation and AD treatment. The design of various functional nanomaterials is discussed, and the strategies for improved properties toward AD treatment are analyzed. Finally, the challenges faced by nanomaterials with different dimensions in AD-related amyloid aggregate modulation are expounded, and the prospects of nanomaterials are proposed.

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1 Introduction

Protein misfolding can form abnormal amyloid aggregates, further leading to amyloid extracellular deposition.¹ These amyloid deposits are widely believed to be closely related to various neurodegenerative diseases and are even considered to be the culprit.² Among them, Alzheimer's disease (AD) is the most common form of neurodegenerative disease, and according to the "2021 World Alzheimer's Disease Report", more than 55 million people worldwide have dementia. This number gets even more staggering as it grows daily and is expected to reach 78 million by 2030.³ Although the pathogenesis of AD has not been clearly confirmed, the amyloid plaque hypothesis has been the most

widely accepted until now.⁴ As the most important component of amyloid aggregates, A β is derived from the sequential proteolytic cleavage of β -amyloid precursor protein (APP) by β - and γ -secretase *in vivo*.⁵ In addition, A β is a hydrophobic peptide with a molecular weight of 4 kDa and consists of 39–42 amino acid residues.^{5,6} The A β monomer undergoes secondary structural transitions and misfolds in physiological environments.⁷ This misfolding A β can rapidly self-assemble with surrounding A β and form oligomers through hydrophobic interactions. Meanwhile, the oligomers can then decrease through the conversion of non-fibrillar to fibrillar oligomers, elongating fibrillar oligomers and finally forming mature amyloid fibrils.⁸ The process of A β aggregation can trigger the production of intra- and extra-cellular reactive oxygen species (ROS), which can lead to oxidation and cellular damage.⁹ In addition, neurotoxicity was induced by A β oligomers and fibrils through binding to the plasma membrane, resulting in metabolic dysfunction and neuronal cell death.¹⁰ Therefore, the inhibition of A β fibrillation, the disintegration of mature A β aggregates, and the promotion of the clearance of A β to maintain the balance of the metabolism and catabolism of A β appear to be quite significant for the prevention and treatment of AD. Recently, numerous efforts have been made to inhibit A β aggregation by blocking fibril formation and reducing the number of fibrils to halt the extent of AD pathology.^{10–12} Among them, nanomaterials have great advantages in influencing amyloid fibril nucleation, disintegrating matured amyloid fibrils, and targeting amyloid plaques *via* crossing the blood–brain barrier (BBB).^{10,13–16} At the same time, nanomaterials have an ability to respond to light, sound, heat, electricity, and magnetism because of the physical properties of

^aDepartment of Chemistry, School of Chemistry and Chemical Engineering, Northwestern Polytechnical University, 127 Youyi Road, Xi'an 710072, China. E-mail: guanping1113@nwpu.edu.cn; huxi@nwpu.edu.cn

^bSchool of Medicine, Xizang Minzu University, Key Laboratory for Molecular Genetic Mechanisms and Intervention Research on High Altitude Disease of Tibet Autonomous Region, Xianyang, Shaanxi 712082, China

^cDepartment of Pharmaceutical Chemistry and Analysis, School of Pharmacy, Air Force Medical University, 169 Changle West Road, Xi'an 710032, China

^dKey Laboratory for Organic Electronics & Information Displays (KLOEID), Institute of Advanced Materials (IAM), Nanjing University of Posts & Telecommunications (NJUPT), Nanjing 210046, China

^eSchool of the Environment, School of Chemistry and Chemical Engineering, State Key Laboratory of Analytical Chemistry for Life Science, State Key Laboratory of Pollution Control & Resource Reuse, Nanjing University, Nanjing, 210023, P. R. China. E-mail: wenleizhu@nju.edu.cn

^fSchool of Mechanical and Materials Engineering, Washington State University, Pullman, WA 99164, USA. E-mail: shichao.ding@wsu.edu

† Xu Shao and Chaoren Yan contributed equally to this work.

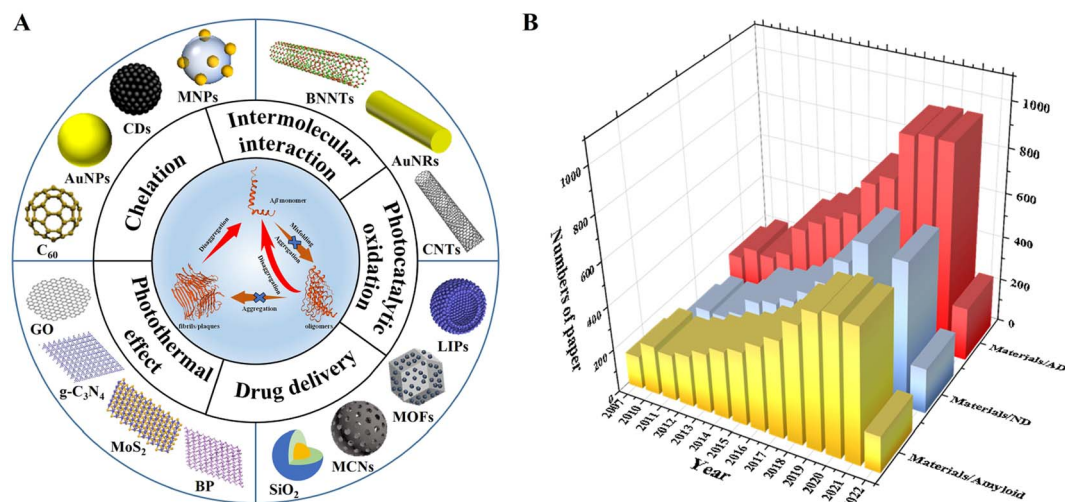


Fig. 1 (A) Schematic illustration of nanomaterials with different functions and dimensions for modulating A β aggregation. (B) The number of published papers per year on the application of nanomaterials in amyloid, neurodegenerative disease (ND), and Alzheimer's disease (AD). Data are collected from the Web of Science on June 26, 2022, by advanced search with "Topics = (Materials and Amyloid; Materials and Neurodegenerative Disease; Materials and Alzheimer's disease; Language: (English))".

some nanomaterials, and they have also been gradually developed and applied in the research of neurodegenerative diseases.^{10,17–21}

Nanomaterials can be classified into one-dimensional, two-dimensional, zero-dimensional, and other nanomaterials according to their dimensions.²² One-dimensional nanomaterials exhibit a high degree of anisotropy, possessing excellent properties such as plasmon resonance, optical properties and anti-oxidation.²³ Two-dimensional nanomaterials have excellent physical and chemical properties, can bind peptides through non-covalent forces, have good biocompatibility, and have good photothermal conversion and photocatalytic capabilities.^{24–26} The large specific surface area of zero-dimensional nanomaterials makes them have unique physical and chemical properties.²⁷ Besides, some composite nanomaterials prepared from other nanocarriers, such as metal–organic frameworks, polyoxometalates, and silica, have multiple synergistic effects.^{28–30} Based on the three-dimensional scale of nanomaterials, this review deeply analyzed the advantages/disadvantages of nanomaterials in modulating amyloid aggregation. The modulation roles of nanomaterials in AD treatment mainly include intermolecular interaction, chelation, photothermal effects, photocatalytic oxidation, and drug delivery (Fig. 1A). As shown in Fig. 1B, we exhibited a number of research articles published each year on the application of nanomaterials in amyloid, neurodegenerative disease (ND), and Alzheimer's disease (AD). This exponential growth of research in the related field indicates that nanomaterials for modulating Alzheimer's related amyloid aggregation are not only an emerging research topic, but also possess huge application potential.

2 One-dimensional nanomaterials

One-dimensional (1D) nanomaterials, including nanorods, nanotubes, nanoribbons, nanowires, and nanofibers, have been

applied as drug carrier or synergistic drug materials.^{31,32} Due to their unique chemical structures, good biocompatibility, high specific surface area, and other related physicochemical properties, 1D nanomaterials were widely applied to the biological field.³³ In recent years, some research showed that 1D nanomaterials with special structures, such as radial size seamless carbon tubes, can interact with amyloid protein and reduce the aggregation of amyloid protein.³⁴

2.1 Carbon nanotubes

Carbon nanotubes with a special structure fabricated from graphene sheets are one-dimensional quantum materials.³⁵ It is mainly composed of several to dozens of layers of coaxial circular tubes of carbon atoms arranged in a hexagonal shape.³⁶ A fixed distance of about 0.34 nm is maintained between layers, and the diameter of nanotubes is generally 2–20 nm.³⁷ According to the different orientations of the hexagon along the axial direction, it can be divided into zigzag, armchair and spiral.³⁸ Single-walled carbon nanotubes (SWCNTs) have been applied in various biological systems because of their good biocompatibility, unique chemical structure, high specific surface area and strong optical absorbance in the near-infrared (NIR) region.³⁹ As unique one-dimensional nanomaterials, SWCNTs have also been explored as novel delivery vehicles for drugs, proteins, and so on.^{40,41} Due to the strong optical absorbance of SWCNTs in the NIR region, SWCNTs could destroy the structure of cells by local thermal during NIR laser irradiation.⁴² As a nanocarrier, SWCNTs were used to deliver oligonucleotides into living cells, and oligos were translocated into cell nuclei upon endosomal rupture triggered by NIR laser pulses.^{43,44} It can be seen that the transporting capabilities of SWCNTs combined with chemical modification and their intrinsic optical properties can lead to new classes of novel nanomedicine for drug delivery and therapy. To the best of our knowledge, SWCNTs have also been

developed for inhibiting amyloid fibrillation, disintegration of amyloid fibrils, and promoting the clearance of amyloid plaques. Luo *et al.*⁴⁵ firstly studied the pH-dependent molecular interactions between SWCNTs and A β peptides by a variety of spectroscopy and atomic force microscopy techniques. They found that the secondary structural transition of A β peptides from a random coil to a β -sheet structure could be significantly affected by SWCNTs, and SWCNTs could inhibit the nucleation/elongation phase of A β peptide fibrillation by adsorbing A β peptides with a β -sheet structure (Fig. 2A). Their research also indicated that A β peptides might reduce the toxicity of SWCNTs by the reduction of the hydrophobic surface of SWCNTs. Wei's group⁴⁶ showed that SWCNTs could inhibit the formation of β -sheet-rich oligomers in the central hydrophobic core fragment of A β (A β_{16-22}). However, a potential problem with SWCNTs is their poor solubility in water and few functional groups, which will cause a huge hindrance to the inhibition of A β fibrillation and other biological applications. Therefore, Xie *et al.*⁴⁷ fabricated a type of hydroxylated SWCNTs by modifying with 30 hydroxyl groups. Then they further investigated the influence of hydroxylated SWCNTs on the aggregation of A β_{16-22} peptides using all-atom explicit-water replica exchange molecular dynamics simulations. The results showed that the β -sheet formation, shift in the conformations and disordered aggregation of A β_{16-22} peptides can be significantly inhibited through hydroxylated SWCNTs, which mainly depend on the strong electrostatic, hydrophobic, and aromatic stacking interactions

with the residue of A β_{16-22} . In addition, Liu *et al.*⁴⁸ also researched the ability of hydroxylated SWCNTs for inhibiting A β aggregation, disaggregating A β fibrils, and protecting A β -induced cytotoxicity. The authors found that SWCNT-OH could inhibit A β fibrillation and disaggregate mature fibrils in a dose-dependent manner (Fig. 2B). Moreover, the related experience showed that the ratio of hydroxyl groups in SWCNT-OH played an important role in inhibiting A β fibrillation. In detail, with the increase the ratio of hydroxyl groups, the inhibitory capacity of SWCNT-OH was greatly improved. Molecular dynamics (MD) simulations further revealed that the interactions between SWCNT-OH and the A β_{11-42} pentamer were found to be dominated by van der Waals interactions. In addition, the inter- and intra-peptide interactions of A β fibrillation were significantly weakened by hydrophobic interactions and π - π stacking of A β and SWCNT-OH, and SWCNT-OH mainly interact with the six residues of A β_{11-42} (H13, H14, Q15, V36, G37, and G38). In our group, the structure of the A β_{42} monomer affected by tuning the curvature of carbon nanotubes was deeply studied using MD simulations.⁴⁹ The related research indicated that A β_{42} peptides had an extended structure and a larger number of contacts with the surface of C25. When the curvatures of the carbon nanotubes (CNTs) were high, the peptide wrapped around the CNTs and had less contact with the surfaces (Fig. 2C). Moreover, the CNTs with lower curvatures and the peptides had stronger interactions and induced the collapse of the initial secondary structures of the peptides. With decreasing curvatures, the

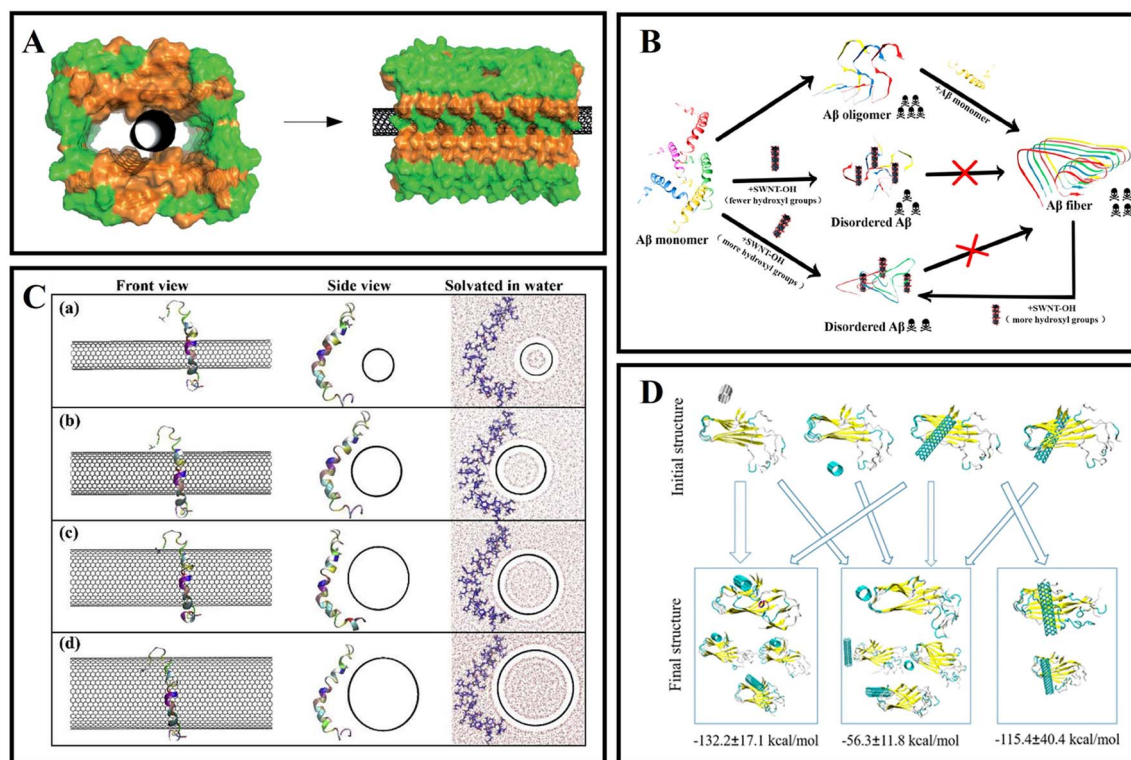


Fig. 2 (A) Illustration of SWCNTs located in the hollow core of A β fibrils.⁴⁵ (B) Hydroxylated SWCNTs inhibit A β_{42} fibrillogenesis and disaggregate mature fibrils.⁴⁸ (C) Initial configurations of the A β_{42} peptide with SWCNT chiralities of (a) (10, 10), (b) (15, 15), (c) (20, 20) and (d) (25, 25).⁴⁹ (D) Disaggregation process of A β_{42} fibrils-SWCNTs in 200 ns.⁵⁰



peptides were arranged diagonally along the nanotube, and the percentages of α -helical structures were reduced. This research indicated that the structural stability, including the nucleation and self-assembly behavior of A β ₄₂ peptides on SWCNT surfaces, is dependent on the surface curvatures. The disaggregation mechanism of SWCNTs for mature A β fibrils was also investigated. For instance, Lin *et al.*⁵⁰ explored the interplay between SWCNTs and A β fibrils by atomic force microscopy, ThT fluorescence, infrared spectroscopy, and MD simulations at the single SWCNT level. The results demonstrated that SWCNTs could partially destroy the mature A β fibrils and form A β -surrounded-SWCNT conjugates and cut down the β -sheet structures. Besides, MD simulation confirmed that the disaggregation ability was dependent on the binding sites of A β fibrils (Fig. 2D).

Compared to SWCNTs, multiwalled carbon nanotubes (MWCNTs) possess obvious advantages, such as lower product cost, excellent chemical stability and drug adsorption potential.⁵¹ Lohan *et al.*⁵² designed a system of berberine (BRB)-loaded MWCNTs with polysorbate and phospholipid coating. BRB was known to possess neuroprotective actions. Polysorbates and phospholipids have been reported to improve the imaging and targeting utility of CNTs. The results showed that the phospholipid-coated and the polysorbate-coated MWCNTs exhibited remarkable recovery in the memory performance.

2.2 Gold nanorods

Gold nanorods are rod-shaped gold nanoparticles with a size ranging from a few nanometers to hundreds of nanometers.⁵³ Gold is a precious metal material with very stable chemical properties. Gold nanoparticles inherit these properties of bulk materials, so they are relatively stable and have very rich physicochemical properties.⁵⁴ The surface plasmon resonance wavelength of gold nanorods can be changed with the aspect ratio, continuously adjustable from visible (550 nm) to near-infrared (1550 nm), and an extremely high surface electric field strength enhancement effect.^{55,56} Gold nanorods have extremely high optical absorption, scattering cross-sections, and photothermal conversion efficiency that is continuously adjustable from 50% to 100%.^{57,58} Therefore, Au nanorods (AuNRs) exhibit strong localized surface plasmon resonance (LSPR) in the near-infrared spectrum and have good performance in photothermal (PTT) therapy.^{59,60}

Gold nanorods as potential therapy nanomaterials have been utilized to modulate amyloid aggregation. AuNRs were functionalized with a metal-chelating group amide-nitrilotriacetic-Co^{II} (ANTACo) to immobilize soluble RepA-WH1 selectively (Fig. 3A). In the presence of catalytic concentrations of anisotropic nanoparticles, H6-RepA-WH1 undergoes stable amyloid oligomerization.⁶¹ Then, such oligomers promote the growth of amyloid fibers of untagged RepA-WH1. Prionoid-functionalized AuNRs as nucleating agents for controlled protein amyloidosis *in vitro*. AuNR-mediated amyloid nucleation is based on a conformational change from the dimer protein precursor to the immobilized pre-amyloidogenic monomer at the nanoparticle surface, which effectively promotes the oligomerization

and fibrillation of amyloid. Lin *et al.*⁶² introduced a novel method where AuNRs combined with A β fibrils can be efficiently destroyed under fs-laser irradiation without increasing the cytotoxicity. The fs-laser could trigger the nanoexplosion of AuNRs by LSPR and bring the A β fibrils into non- β -sheet structure components. Sudhakar *et al.*⁶³ fabricated AuNRs and utilized them to inhibit the aggregation of A β by a NIR laser. Meanwhile, the shape-dependent plasmonic properties of AuNRs are exploited to facilitate faster disaggregation of mature A β fibrils. In addition, a related study found that 1,2-dimyristoyl-*sn*-glycero-3-phosphocholine (DMPC) stabilized AuNRs can inhibit the formation of fibrils due to selective binding to the positively charged amyloidogenic sequence of A β protein (Fig. 3B). This research exhibited a dual effect: inhibition of A β fibrillation and NIR laser facilitated the dissolution of mature A β fibrils. However, the role of heat generation by AuNRs, which promoted the disaggregation of fibrils, had not been explained from a molecular perspective.⁶³ Then Liu *et al.*⁶⁴ prepared CTAB-stabilized AuNRs with different sizes (CTAB as cetyltrimethylammonium bromide), and the effect of diameters and lengths of AuNRs on A β fibrillation was in-depth studied. A related fluorescence experiment indicated that in the presence of CTAB-stabilized AuNRs with different sizes, the formation of larger oligomers and fibrils was inhibited, and the inhibition efficiency decreased with the decrease of diameters of AuNRs (Fig. 3C). For the AuNRs with the same diameter, the inhibition efficiency decreased with the length of Au NRs. A CD experiment indicated that AuNRs with larger sizes inhibited the formation of a β -sheet structure to some extent. In summary, CTAB-stabilized AuNRs inhibited the kinetic process of A β fibrillation, and the inhibition efficiency of larger AuNRs was better. Meanwhile, the sizes of AuNRs played a key role in modulating the kinetic aggregation process of A β fibrillation. This work found that the rate constant had a positive relationship with the diameters or lengths of CTAB-stabilized AuNRs. Interestingly, Liu *et al.*⁶⁵ studied the NIR absorption properties of AuNRs loaded with a single chain variable fragment and thermophilic acylpeptide hydrolase as a smart theranostic complex GAS, which possesses both rapid detection of A β aggregates and NIR photothermal treatment that effectively disaggregates A β aggregates and reduces A β -mediated toxicity (Fig. 3D). Morales-Zavala *et al.*⁶⁶ synthesized a polyethylene glycol stabled and dual-peptide modified gold nanorod complex. A related study determined that the nanoconjugate does not affect neuronal viability. The nanoconjugate could penetrate the cells and decrease the A β peptide aggregation *in vitro*. Subsequently, Morales-Zavala *et al.*⁶⁷ also developed a neurotheranostic platform based on AuNRs, which works as a therapeutic peptide delivery system. As a diagnostic tool, the platform could be detected *in vivo* through microcomputed tomography (micro-CT). Ang2 and D1 peptide modified AuNRs induced the diminution of both the amyloid load and inflammatory markers in the brain of the AD model. The differences in GNRs-D1/Ang2 between wild type (WT) and AD mice were observed *in vivo*. The two peptide modified AuNRs can improve the delivery and retention of this platform in the brain and reinforce the



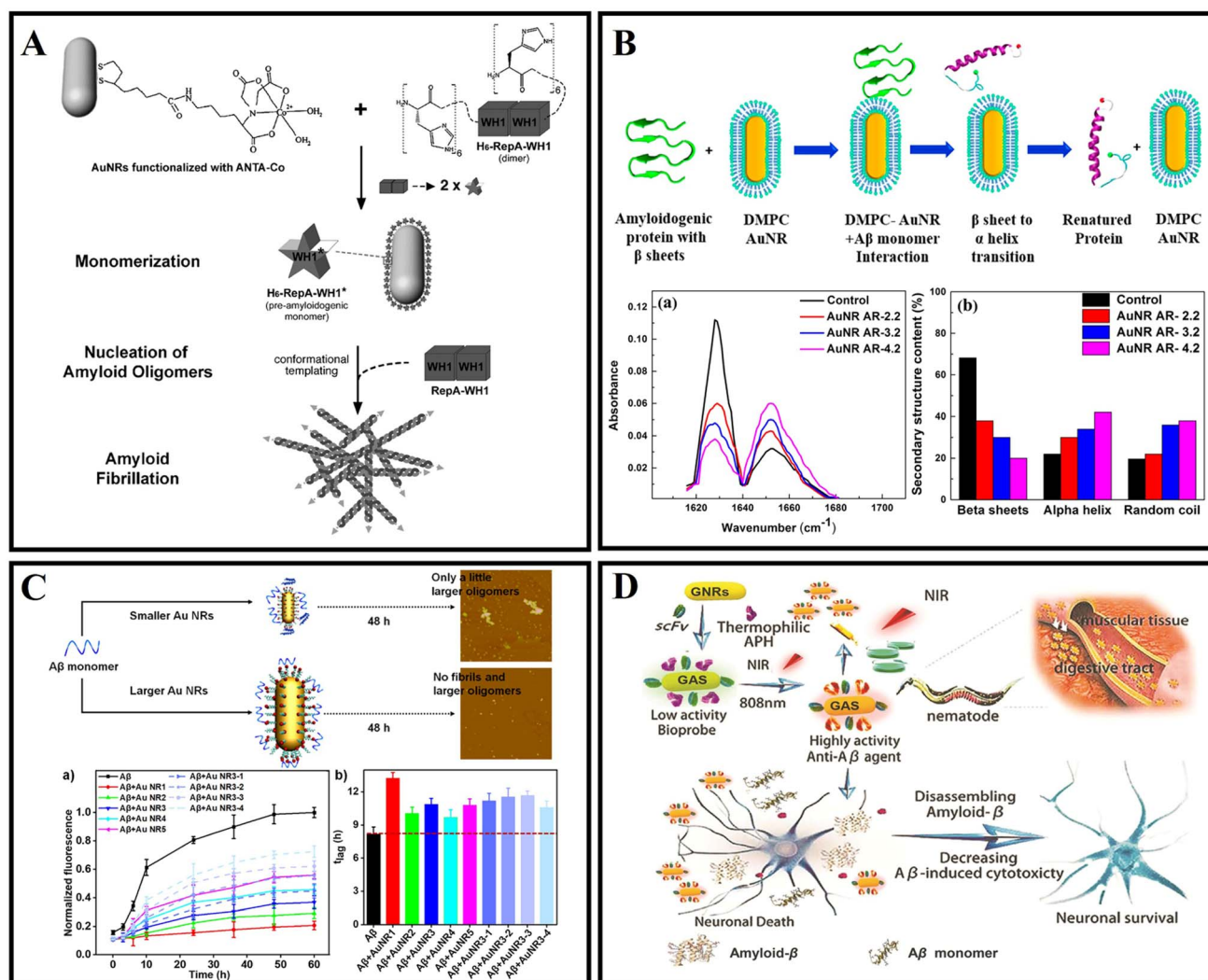


Fig. 3 (A) Illustration of the nucleation of RepA-WH1 amyloidogenesis by prionoid-functionalized AuNRs.⁶¹ (B) Interaction between AuNRs and Aβ protein monomer and conversion of the β-sheet to an α-helix secondary structure.⁶³ (C) CTAB-stabilized AuNRs with different sizes inhibiting Aβ peptide aggregation.⁶⁴ (D) The GAS with NIR absorption is used for AD diagnosis and treatment.⁶⁵

therapeutic benefits associated with the β-sheet breaker ability of the D1 peptide.

3 Two-dimensional nanomaterials

Two-dimensional (2D) nanomaterials refer to nanomaterials that have only one dimension on the nanometer scale.⁶⁸ Because of their huge specific surface area and special surface structure, 2D nanomaterials can adsorb and interact with various molecules such as drugs, nucleic acids, peptides, and proteins.⁶⁹ Two-dimensional nanomaterials also have the ability to penetrate biological barriers.⁷⁰ Therefore, as a drug carrier, 2D nanomaterials can load numerous drugs and cross various biological barriers.^{71,72} Meanwhile, 2D nanomaterials can also absorb and immobilize amyloid protein by interacting with interfaces.⁷³ Some 2D nanomaterials possess light-responsive properties and have great potential in photothermal and photodynamic therapy.^{69,74} Two-dimensional nanomaterials

have good peroxidase-like properties and can alleviate oxidative stress.⁷⁵ Based on the advanced properties, 2D nanomaterials have been attractive in AD diagnosis and treatment.⁷⁶ 2D nanomaterials have been used in AD research, mainly including graphene nanosheets, carbon nitride nanosheets, black phosphorus nanosheets, and transition metal dichalcogenide nanosheets. Besides, some studies have shown that 2D MOFs, MXenes, hexagonal boron nitride and so on also have applications in AD diagnosis and treatment.

3.1 Graphene

Graphene or graphene oxide (GO), one of the two-dimensional nanomaterials, consists of mono-layer carbon atoms with conjugated π-π.⁷⁷ Due to the excellent electrical conductivity, ultra-high specific surface area, high mechanical strength, good biocompatibility, and photothermal conversion characteristics, graphene has been widely used in biomedical fields such as bioimaging, biosensing, and drug delivery.^{78–80}



Mahmoudi *et al.*⁸¹ indicated that GO and protein-coated GO can delay the A β fibrillization process *via* adsorption of amyloid monomers. Then Li *et al.*⁸² further confirmed that the binding between the peptide monomer and the surface of the GO sheets can redirect the assembly pathway of A β (Fig. 4A). Wang *et al.*⁸³ examined the size effect of GO on modulating amyloid peptide assembly and found that GO with a large size has a relatively stronger modulation effect for the aggregation of A β_{33-42} . The advantages of graphene nanocomposites are even more obvious. As shown in Fig. 4B, Ahmad *et al.*⁸⁴ successfully fabricated nanocomposites of iron oxide and graphene oxide (GOIO) using solvothermal methods. Due to the high surface area of GOIO, GOIO can effectively interact with A β_{42} , inhibit the formation of mature fibrils from A β_{42} monomers and maintain the secondary structure of A β_{42} into a random coil or α -helix-rich structure. Many researchers have worked to investigate the mechanism of action of graphene bias with A β . The

penetration and extraction of graphene were identified as two main mechanisms for scavenging fibrils (Fig. 4C).⁸⁵ This is because of the strong interaction between graphene and amyloid fibrils through π - π stacking and hydrophobic interaction due to the special sp^2 structure of graphene. Graphene nanosheets can extract single peptide molecules from mature amyloid fibrils into their surface, and the absorption interaction is further enhanced by π - π stacking because of the aromatic residues of A β and the sp^2 structure of graphene. Chen *et al.*⁸⁶ investigated the oligomerization of A β_{33-42} by performing replica exchange MD simulations on A β_{33-42} peptide chains in the absence and presence of two different sizes of GO, and found that GO inhibited A β_{33-42} oligomerization by making A β_{33-42} peptides separate from each other. Jin *et al.*⁸⁷ revealed the mechanism of GO nanosheets in inhibiting A β_{42} aggregation through MD simulations, and found that GO mostly suppressed the β -sheet formation of A β_{42} by weakening inter-

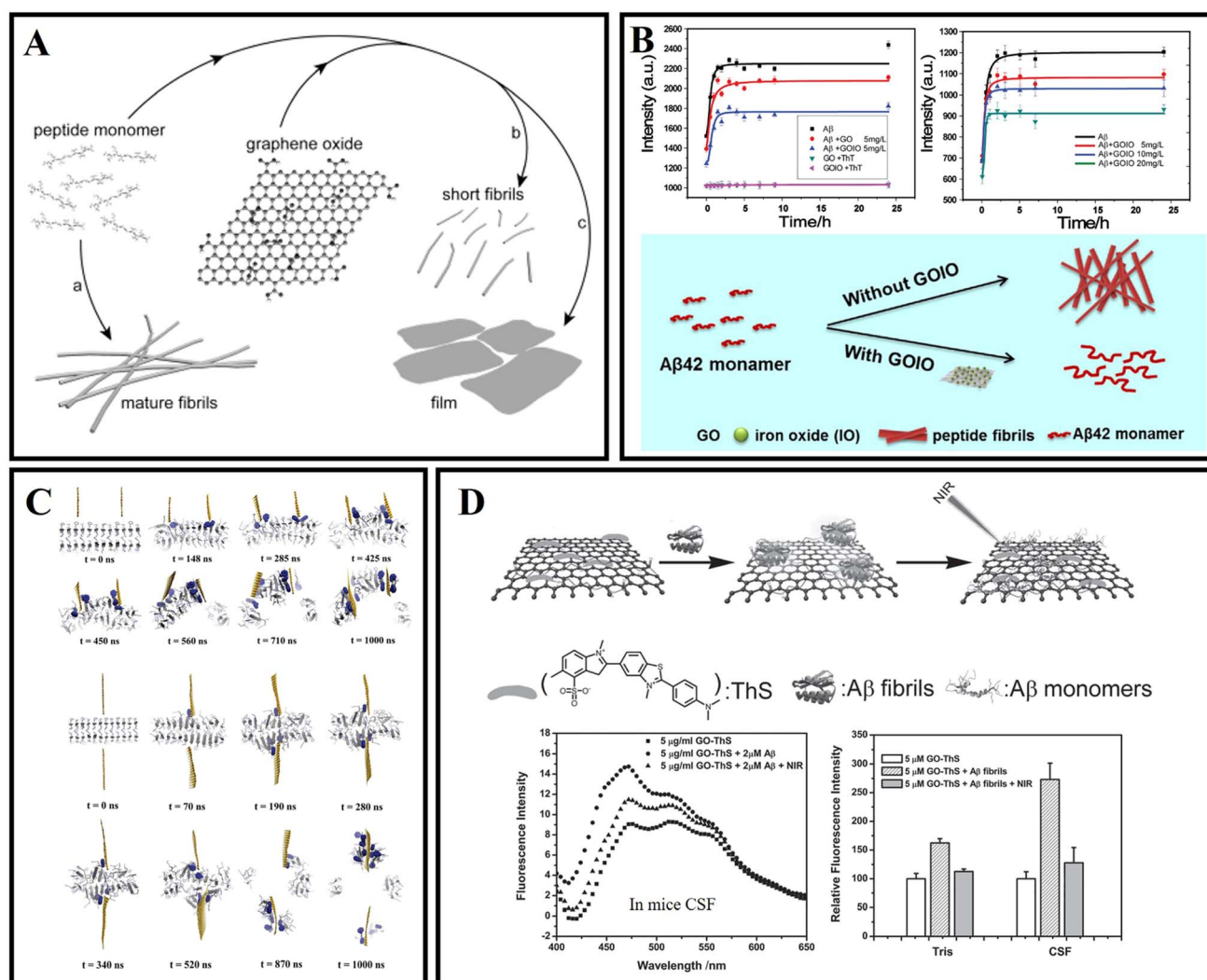


Fig. 4 (A) The surface of graphene-oxide sheets redirects the amyloid-peptide assembly process.⁸² (B) Kinetics of A β_{42} fibrillation and illustration of modulation of A β_{42} aggregation by using GOIO.⁸⁴ (C) Graphene nanosheet penetration and A β peptide extraction. Featuring two graphene sheets attacking a pre-formed A β amyloid fibril from the same side, and the two graphene sheets attacking from both sides.⁸⁵ (D) GO-ThS effectively dissolve the amyloid deposits of A β_{40} upon NIR laser irradiation.⁹¹

peptide interactions mostly *via* the salt bridge, hydrogen bonding and cation- π interactions with charged residues D1, E3, R5, D7, E11, K16, E22, K28 and A42. The π - π and hydrophobic interactions between GO and A β ₄₂ also play a key role in the inhibition of A β aggregation. Meanwhile, Yin *et al.*⁸⁸ indicated that the adsorption capacity with A β of graphene's surface varies significantly depending on its curvature. The negative curved surface is more likely to adsorb A β than the positive curved surface. These findings showed that the shape of the nanoparticle is important in determining its interaction with the peptide. He *et al.*⁸⁹ investigated the thermodynamics and kinetics of fibril elongation on GO surfaces with different oxidative degrees. This study revealed that the behaviors of GO in fibril elongation depend on the balance between the promoting effect by templating the incoming of monomers and the retarding effect by capturing the monomer during docking and locking phases through hydrogen bonding. Subsequently, Li *et al.*⁹⁰ also further demonstrated that GO could clear amyloids by inducing microglia and neuron autophagy. Photothermal therapy can be used to dissolve mature A β fibrils. As shown in Fig. 4D, Qu's group firstly reported the photothermal treatment for AD using graphene nanosheets. Thioflavin S (ThS) which can specifically bind to A β fibers was covalently linked to the surface of GO. The prepared GO-ThS nanocomposites have a uniform diameter of 100 to 200 nm, and the thickness of GO-ThS nanocomposites is about 1.5 nm. The related research showed that GO-ThS can cross the BBB, selectively interact with A β ₄₀ fibrils, and disaggregate A β ₄₀ fibrils under near-infrared (NIR) laser irradiation. Moreover, the decomposition of A β ₄₀ fibrils can be monitored by the fluorescence changes of ThS in real time.⁹¹ Xia and Maciel *et al.*^{92,93} have reported a potential drug carrier for loading drugs using GO through non-covalent interactions. Wang *et al.*⁹⁴ prepared a novel nanocomposite GO@Dau from GO and dauricine (Dau), and the benzene ring on Dau can be adsorbed by GO by forming a non-covalent bond. GO@Dau will both have anti-inflammatory and anti-oxidative stress capabilities and inhibit A β misfolding. This study further found that GO@Dau can effectively enrich in the brain after intranasal administration and GO@Dau can be internalized into the olfactory bulb by endocytosis or pinocytosis of olfactory neurons, and then released and distributed into the brain. More interestingly, researchers found that GO@Dau could increase superoxide dismutase levels, decrease reactive oxygen species and malondialdehyde levels *in vitro*, and attenuate cognitive memory deficits and glial cell activation for AD mice.

Overall, graphene nanosheets and their nanocomposites have been reported for use in AD therapy. However, the specific-targeted issue and drug delivery modalities of graphene still need to be elucidated. Especially, the BBB penetration of graphene is needed to be deeply researched. Through functionalization and size or shape adjustment for nanomaterials, utilizing paracellular pathway, transcellular lipophilic pathway, transport proteins, receptor-mediated transcytosis, and adsorptive-mediated transcytosis could achieve penetration of the BBB.^{95,96} Although many investigators have studied and summarized the biodistribution characteristics, *in vivo*

clearance, toxicity, and interactions with biological systems of GO, there is still much to be unveiled that would allow safe and effective therapy.^{97,98}

3.2 g-C₃N₄

Graphitic carbon nitride (g-C₃N₄) is the most stable allotrope of carbon nitride under ambient conditions.⁹⁹ g-C₃N₄ has thermodynamic stability, good biocompatibility, low toxicity, and unique photocatalytic properties.^{100–102} It has received extensive attention in biological applications in recent years.¹⁰³

In 2016, Li *et al.* firstly used g-C₃N₄ as an A β inhibitor for AD treatment.¹⁰⁴ As shown in Fig. 5A, g-C₃N₄ nanosheets could effectively inhibit the formation of A β aggregates, separate the preformed A β -Cu²⁺ aggregates, and reduce the intracellular reactive oxygen species (ROS) levels. Then, Li *et al.*¹⁰⁵ combined the advantages of g-C₃N₄ nanosheets with some metal complexes to fabricate platinum(II)-coordinated g-C₃N₄ nanosheets (g-C₃N₄@Pt), and g-C₃N₄@Pt was able to inhibit A β fibrillation. As shown in Fig. 5B, g-C₃N₄@Pt could effectively inhibit the aggregation of A β through non-covalent interaction and photooxidation. As shown in Fig. 5C, Wang *et al.*¹⁰⁶ prepared a nanocomposite which is named GO/g-C₃N₄ by the sonochemical method. Under UV light irradiation, GO/g-C₃N₄ could disaggregate mature A β fibrils. GO could act as an A β collector by adsorption interaction and g-C₃N₄ could serve as a cleaner by photodegradation. Notably, the photodegradation efficiency of the composite could be kept high because the heterojunction between GO and g-C₃N₄ helps to separate the photoexcited electron-hole pairs. In 2020, Wang *et al.*¹⁰⁷ reported a kind of novel gold nanoparticle modified g-C₃N₄ (Au/g-C₃N₄), which can effectively degrade preformed amyloid aggregates, and the photodegradation of amyloid aggregates mainly depends on the generation of oxygen radicals, especially hydroxyl radicals. As shown in Fig. 5D, Chung *et al.*¹⁰⁸ verified that g-C₃N₄ can effectively inhibit the aggregation of A β under light illumination. Under visible light irradiation, g-C₃N₄ nanosheets could generate ROS through photo-induced electron transfer, and oxidize A β protein, preventing A β misfolding and fibrillation. The inhibition efficiency of g-C₃N₄ for A β aggregation will be increased with the concentration and absorbance intensity of g-C₃N₄ under LED irradiation. Doping metal ions, such as iron, can help g-C₃N₄ nanosheets accelerate the charge transfer activity, resulting in high ROS generation for inhibiting A β aggregation.¹⁰⁹

g-C₃N₄ has some inherent disadvantages, such as poor water solubility, relatively large particle size, and lack of absorption above 460 nm, but its reliable biocompatibility at certain doses proves its potential for biological applications.^{110–112} For g-C₃N₄ applications in living organisms, issues such as autofluorescence, optical therapeutic efficiency, and *in vivo* clearance rates still need to be addressed.¹⁰³

3.3 Black phosphorus

Black phosphorus (BP) nanosheets, a novel two-dimensional layered semiconductor nanomaterial, have attracted extensive attention due to their good optical, thermal properties,



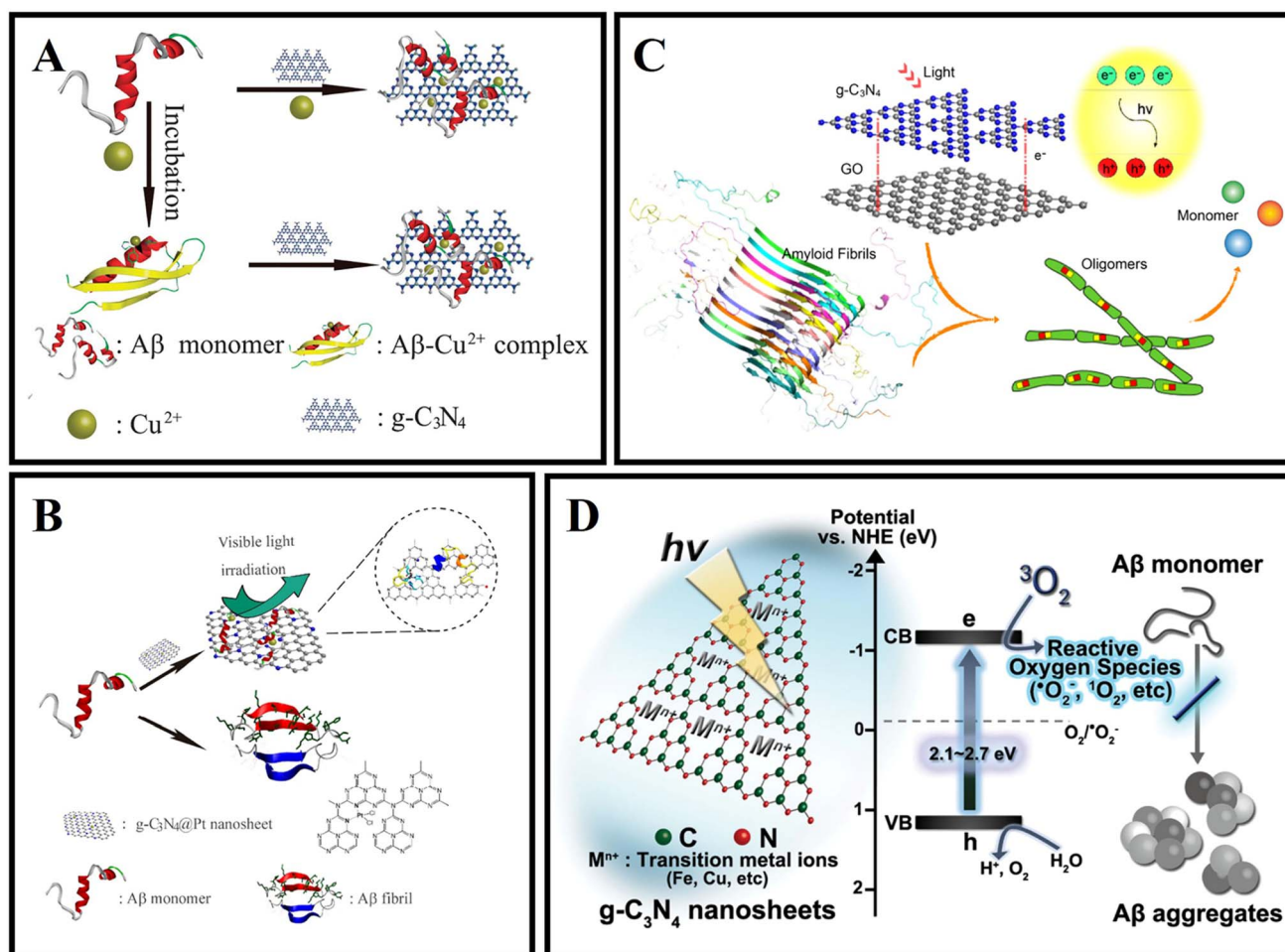


Fig. 5 (A) The ultrathin g-C₃N₄ nanosheets can effectively inhibit Cu²⁺ induced Aβ aggregation and disaggregate the preformed Aβ-Cu²⁺ aggregates.¹⁰⁴ (B) g-C₃N₄@Pt was used for AD treatment.¹⁰⁵ (C) The disaggregation of Aβ aggregates by GO/g-C₃N₄ under light irradiation.¹⁰⁶ (D) Highly reactive ROS trigger peptide oxidation that suppresses further fibril formation of Aβ.¹⁰⁸

photocatalytic properties, and biological compatibility.^{113,114} BP can be degraded into non-toxic phosphate and phosphite anions under physiological conditions.¹¹⁵ BP nanosheets can efficiently and selectively capture Cu²⁺ to protect neuronal cells from Cu²⁺-induced neurotoxicity.¹¹⁶ Moreover, due to the photothermal transition efficiency, BP nanosheets can cross the BBB by relying on NIR laser irradiation.¹¹⁷

In 2019, Lim *et al.*¹¹⁸ synthesized two kinds of typical BP nanomaterials with different sizes, titanium ligand-modified BP nanosheets (TiL₄@BPNSs) and titanium ligand-modified BP quantum dots (TiL₄@BPQDs). The results showed that TiL₄@BPNSs and TiL₄@BPQDs inhibited Aβ₄₀ aggregate by adsorbing Aβ₄₀ monomers. Then, Yang *et al.*¹¹⁹ designed a PEG-stabilized BP nano-system PEG-LK7@BP, which can effectively inhibit the formation of Aβ₄₂ fibrils (Fig. 6A). In addition, as a peptide inhibitor, LK7 was coupled to the BP surface *via* electrostatic and p-π interactions. PEG was used to enhance the stability of BP. PEG-LK7@BP inhibited Aβ₄₂ fibrillation in a dose-dependent manner. Importantly, PEG-LK7@BP has no cytotoxicity to normal cells and can effectively alleviate the cytotoxicity induced by Aβ. The inhibition ability of PEG-LK7@BP

can be attributed to multiple effects: (1) PEG-LK7@BP can bind with Aβ through electrostatic and hydrophobic interactions. (2) LK7 can enhance the targeted properties of PEG-LK7@BP for Aβ amyloid. (3) PEG enhanced the stability and dispersibility of the nanomaterials. Cu²⁺ can catalyze the production of ROS and cause neuronal apoptosis.¹²⁰ Therefore, it is needed to design novel nanomaterials for not only capturing excess metals but also crossing the BBB. As shown in Fig. 6B, Chen *et al.*¹²¹ demonstrated that BP nanosheets can efficiently and selectively chelate Cu²⁺ to inhibit neurotoxicity induced by Cu²⁺. Importantly, under the irradiation of a NIR laser, the BBB permeability of BP nanosheets is significantly improved due to the photothermal effect.

Due to the properties of precise treatment and fewer side effects for various diseases, photodynamic therapy (PDT) has attracted extensive attention in the biomedical field.^{122,123} However, some photosensitizers suffer from low catalytic efficiency, a short absorption wavelength, poor biocompatibility, and non-degradability in living tissues.¹²⁴ In 2015, Wang *et al.*¹²⁵ first demonstrated that exfoliated BP nanosheets are effective photosensitizers for generating ¹O₂, and the quantum yield is

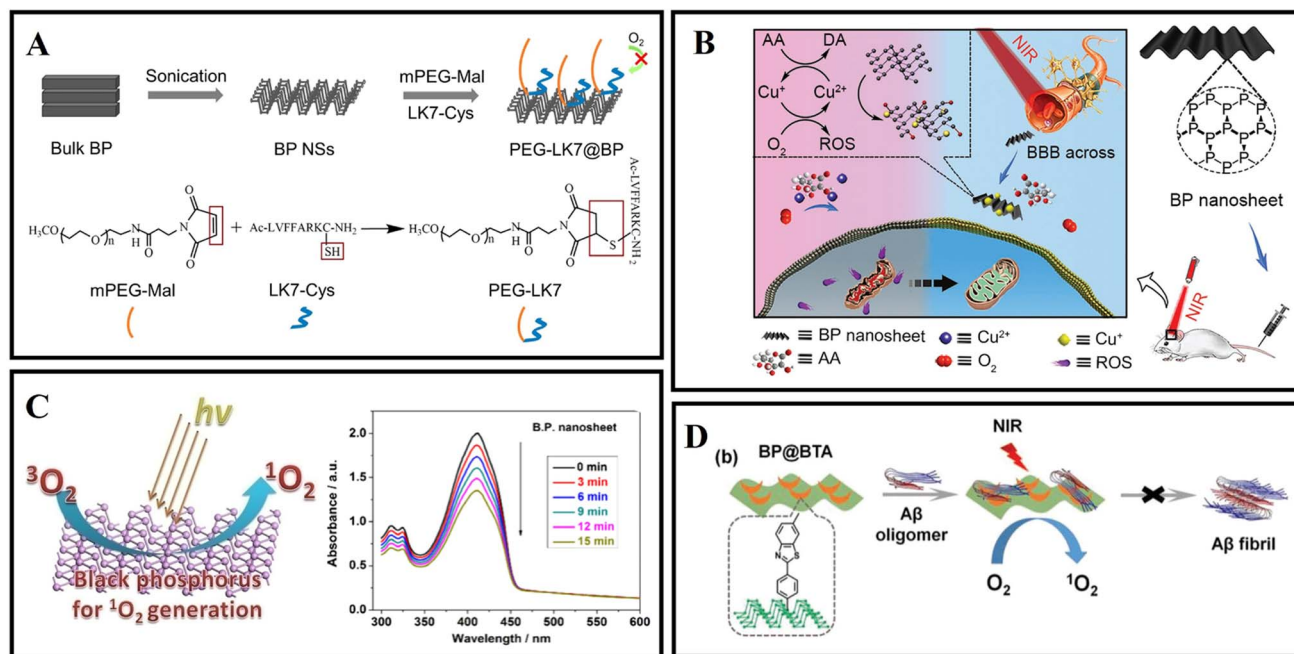


Fig. 6 (A) The preparation of PEG-LK7@BP and the reaction of mPEG-Mal with LK7-Cys during PEG-LK7@BP formation.¹¹⁹ (B) BP nanosheets as a BBB penetrable nanocaptor to reduce oxidative stress production through capturing Cu ions.¹²¹ (C) Ultrathin BP nanosheets for efficient singlet oxygen generation.¹²⁵ (D) BP@BTA produced ¹O₂ under NIR to inhibit Aβ aggregation.¹²⁶

about 0.91 (Fig. 6C). These excellent properties make BP nanosheets photocatalysis nanomaterials in PDT therapy. As shown in Fig. 6D, Qu's group designed a near-infrared responsive nanomaterial based on BP nanosheets.¹²⁶ The authors also utilized BTA (one of the thioflavin-T derivatives) to modify black phosphorus, aiming to recognize Aβ and enhance BP stability. BP@BTA could generate ¹O₂ efficiently and the inhibition efficiency of Aβ fibrillation was effectively heightened.

Compared with other 2D materials, BP exhibits a tunable energy bandgap from about 0.3 eV (bulk) to 2.0 eV (monolayer), allowing broad absorption across the entire ultraviolet and infrared regions.^{127,128} Moreover, the degradable character of BP from element to nontoxic and biocompatible phosphorus oxides is endowed with good biocompatibility *in vivo*.¹²⁹

3.4 Transition metal dichalcogenides

Different from carbon or phosphorus-based two-dimensional (2D) nanomaterials, transition metal dichalcogenide nanosheets have become alternative candidates, such as MoS₂ and WS₂. MoS₂ and WS₂ are sandwich structures composed of hexagonal metal atoms sandwiched between two layers of chalcogens.¹³⁰ Transition metal dichalcogenide nanosheets were shown to address biological and medical fields due to their novel nanoscale structures, rich physics, and high mobility.^{131–133} The basal plane of transition metal disulfide nanosheets can adsorb or conjugate various aromatic hydrocarbons (such as pyridine and purine) and other compounds.¹³⁴ In recent years, transition metal dichalcogenide nanosheets have been reported for drug delivery and tissue ablation.¹³⁵

In 2013, Chou *et al.*¹³⁶ prepared MoS₂ by a chemical exfoliation method and obtained a two-dimensional amphiphilic compound with good colloidal stability in aqueous media. Wang *et al.*¹³⁷ explored the effect of MoS₂ on the fibrillation process of Aβ fragments and human islet amyloid polypeptide (hIAPP) fragments. A related study found that MoS₂ allows for concentration-dependent modulation of amyloid aggregation. Mudedla *et al.*¹³⁸ applied MD simulations to deeply study the interaction mechanism between amyloid fibrils and MoS₂-based nanomaterials. MoS₂-based nanomaterials cause the disruption of the secondary structure and change the β-sheet conformation to a flipped form. The results exhibited that the intermolecular force of peptides, including hydrophobic and hydrophilic interactions, was reduced due to the interaction between peptide and molybdenum disulfide materials. More destabilization of the fibril under nanotubes is observed compared to the nanosurfaces due to the difference in binding modes (Fig. 7A). Regrettably, no corresponding *in vivo* studies were performed. Liu *et al.*¹³⁹ studied the effect of gold nanoparticle-doped molybdenum disulfide (AuNP-MoS₂) nanocomposites on the aggregation of Aβ₄₀. Low concentrations of AuNP-MoS₂ can enhance the nucleation of Aβ₄₀ and accelerate the aggregation of Aβ₄₀. Although high concentrations of AuNP-MoS₂ can enhance the nucleation of Aβ₄₀ protein, it ultimately inhibits the Aβ₄₀ aggregation process (Fig. 7B). It may be attributed to the interaction between AuNP-MoS₂ and Aβ₄₀ protein. A low concentration of AuNP-MoS₂ can act as a nucleus. As the concentration of AuNP-MoS₂ was increased, the structural transformation of the Aβ₄₀ peptide was limited, leading to efficient inhibition of Aβ₄₀ aggregation. MoS₂ can rapidly heat up under NIR irradiation so that MoS₂ can be used for



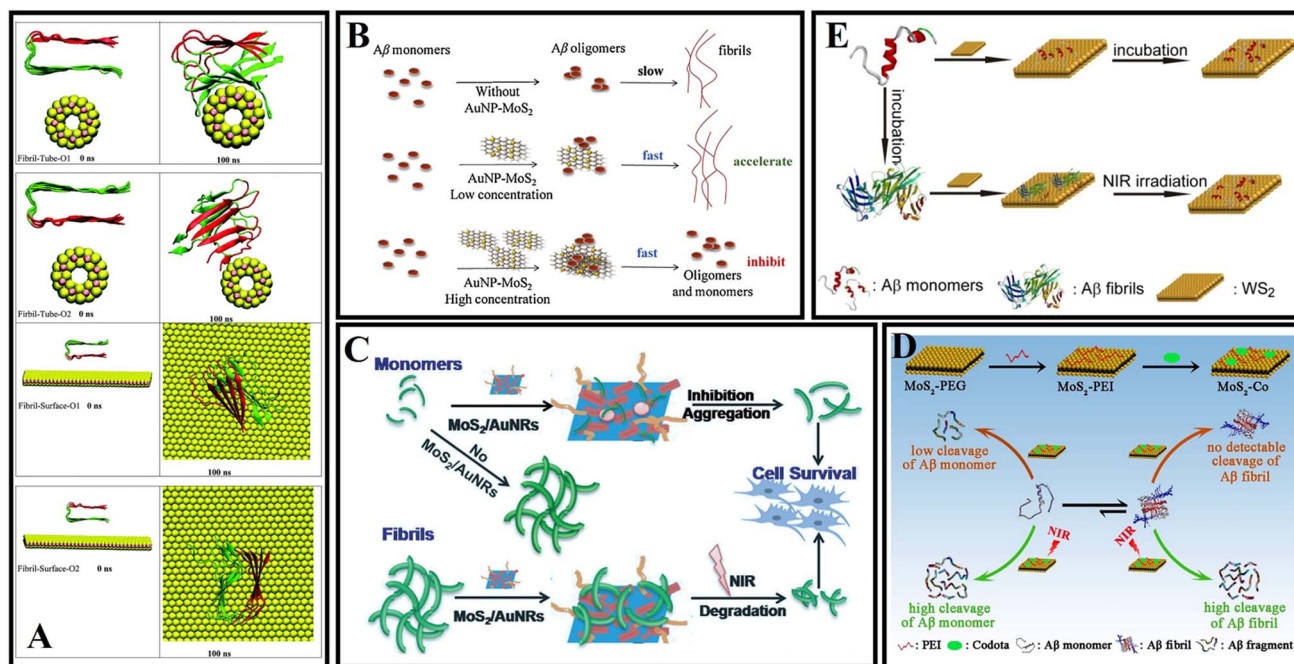


Fig. 7 (A) Initial and final snapshots of the interaction between amyloid fibrils and MoS₂ nanomaterials.¹³⁸ (B) Concentration-dependent mechanism of AuNP-MoS₂ nanocomposites in Aβ₄₀ aggregation.¹³⁹ (C) MoS₂/AuNR nanocomposites with high NIR absorption were used for inhibiting β-amyloid aggregation.¹⁴⁰ (D) MoS₂-Co improved the hydrolytic activity toward Aβ monomers and enhanced the hydrolytic capacity toward Aβ fibrils in the presence of a NIR laser.¹⁴¹ (E) WS₂ nanosheets with high NIR absorbance are used for AD treatment.¹⁴²

photothermal therapy. Wang *et al.*¹⁴⁰ designed multifunctional MoS₂/AuNRs through the combination of MoS₂ nanosheets and AuNRs. MoS₂/AuNR can disrupt mature fibrils under NIR irradiation and prevent Aβ protein-induced neurotoxicity. It is worth mentioning that both MoS₂ nanosheets and AuNRs can be used as NIR photothermal agents, and the MoS₂/AuNR nanocomposites enhance the ability to destroy Aβ fibrils and enhance cell viability by generating localized heat under NIR irradiation (Fig. 7C). Because the specific cleavage sites of Aβ are often embedded in the β-sheet structure, artificial enzyme inhibition efficiency is severely hindered in practical applications. Qu's group constructs a NIR controllable artificial metalloprotease (MoS₂-Co) using a MoS₂ nanosheet and a cobalt complex of 1,4,7,10-tetraazacyclododecane-1,4,7,10-tetraacetic acid (Codota).¹⁴¹ MoS₂-Co circumvented the β-sheet structural restrictions by simultaneous inhibition of the conformational switch from the random-coil to β-sheet structures and modulation of β-sheet structures of the preformed Aβ fibrils (Fig. 7D).

Li *et al.*¹⁴² found that WS₂ nanosheets could effectively inhibit Aβ₄₀ aggregation. Under van der Waals forces and electrostatic interactions, Aβ₄₀ monomers can be selectively adsorbed on the nanosheet surface. WS₂ has high NIR absorption properties, which can dissociate Aβ₄₀ fibrils under NIR irradiation (Fig. 7E). Compared with traditional small molecular Aβ inhibitors, WS₂ nanosheets can cross the BBB and exhibit excellent physicochemical characteristics.

The synthesis and modification methods of transition metal dichalcogenide nanosheets need to be further optimized. The preparation of nanosheets of specific thickness and size is

essential. In addition, targeting issues and the biodegradation behavior of nanosheets need to be further explored.

3.5 Others

2D COFs, MXenes, hexagonal boron nitride and so on have also been reported for use in AD diagnosis and treatment.^{120,143,144}

Covalent organic frameworks (COFs) are a new generation of nanoparticles consisting of carbon, oxygen, nitrogen and hydrogen atoms with excellent biocompatibility.¹⁴⁵ 2D COFs have a highly tunable structure and can be designed to cross the blood-brain barrier and inhibit Aβ aggregation. Maleki *et al.*¹⁴³ combined experimental and molecular simulation tools to investigate the interaction of novel two-dimensional COF materials with Aβ. The results indicate that amine-functionalized COFs with large surface areas have the potential to inhibit Aβ aggregation. Amine-functionalized groups were also found to enhance the ability of COFs to break the BBB. Two-dimensional transition metal carbides and/or nitrides (MXenes) possess a variety of enzyme-mimetic activities such as superoxide dismutase (SOD), catalase (CAT) and peroxidase (POD), which can be used for ROS scavenging against oxidative stress-induced inflammation and neurotoxicity. MXenes have good photothermal properties and improve the permeability of the BBB. Du *et al.*¹²⁰ engineered 2D ultrathin Nb₂C nanosheets to chelate metal ions and alleviate oxidative stress. *In vitro* experiments and theoretical calculations have demonstrated the antioxidant properties of Nb₂C MXenzyme nanosheets and their specific chelating effect on Cu²⁺. In addition, the

Table 1 A list of two-dimensional inhibitors for the modulation mechanism and effect of amyloid aggregation

Nanomaterials	Modulation mechanism	Effect	Ref.
GO	Adsorption/size effect	Delay	85
GO-ThS	Photothermal	Disaggregation	91
GOIO	Adsorption	Inhibition	84
GO@Dau	Adsorption/anti-oxidation	Inhibition/disaggregation	94
g-C ₃ N ₄	Chelation	Inhibition/disaggregation	108
g-C ₃ N ₄ @Pt	Noncovalent interactions/platinum coordination/photooxygenation	Inhibition/disaggregation	105
Au/g-C ₃ N ₄	Photooxygenation	Disaggregation	104
GO/g-C ₃ N ₄	Photooxygenation	Disaggregation	106
g-C ₃ N ₄	Photooxygenation	Inhibition	107
BP	Adsorption	Regulate the aggregation	118
PEG-LK7@BP	Electrostatic/hydrophobic interactions	Inhibition	119
BP@BTA	Photooxygenation	Inhibition	126
MoS ₂	Adsorption	Modulation	137
MoS ₂ -Co	Photothermal	Inhibition/disaggregation	141
MoS ₂ /AuNR	Photothermal	Modulation/disaggregation	140
AuNPs-MoS ₂	Concentration	Acceleration/inhibition	139
WS ₂	Photothermal/van der Waals/electrostatic interactions	Inhibition/disaggregation	142
2D COFs	van der Waals/electrostatic interactions/hydrogen bonds	Acceleration/inhibition	143
MXene	Chelation	Reducing ROS levels	120
BNNS	Adsorption	Modulation	144

photothermal conversion properties of Nb₂C MXene nano-sheets give them the ability to cross the BBB non-invasively.

Boron nitride nanomaterials have good chemical stability, antioxidant properties and biocompatibility. Unlike carbon nanomaterials, boron nitride nanomaterials are less hydrophobic and can maintain the conformation of A β rather than change it. Sorout *et al.*¹⁴⁶ found that the interpeptide contacts are largely reduced in the presence of (3,3) boron nitride nanotube (BNNT) and that the nanoparticle interacts with the trimer in such a way that the initial helical secondary structure of the A β peptide is retained. The effect of different curvatures of boron nitride on A β aggregation was then continued to be investigated. And it was found that the planar boron nitride nanosheet (BNNS) with zero curvature is found to prevent β -sheet formation by converting the secondary structure of the peptide to dominant coil and turn conformations.¹⁴⁴ The total number of peptide-nanoparticle contacts increases with a decrease in the curvature and a corresponding increase in the nanoparticle surface area. In addition, boron nitride nanoparticles have been reported as nanocarriers/agents to ameliorate A β -induced cytotoxicity.^{147,148} Currently for boron nitride nanomaterials differences from carbon nanomaterials have been revealed. Further research is expected to lead to a new generation of AD therapeutic nano-agents. Table 1 lists the mechanism and effect of two-dimensional inhibitors on the modulation of amyloid aggregation.

4 Zero-dimensional nanomaterials

Zero-dimensional (0D) nanomaterials, including gold nanoparticles (GNPs), gold nanoclusters, organic and inorganic quantum dots, metal oxide nanoparticles, and carbon-based nanomaterials, have attracted extensive research interest in the field of biomedicine in recent years.¹⁴⁹ The edge effect,

quantum confinement effect, ultra-small size and good biocompatibility of 0D nanomaterials endow them with many functions and special performance, such as photoluminescence (PL), tissue penetration, bioactivity, and drug loading capability.¹⁴⁹ Therefore, various 0D nanomaterials have been applied to diagnose and treat diseases, such as neurodegenerative disease, cancer and infection.¹⁵⁰ Moreover, some advanced 0D nanomaterials can overcome the BBB and inhibit AD-related amyloid aggregation, so they are utilized to treat Alzheimer's disease.^{151–153} In this part, we summarized diverse treatment methods for amyloid and related neurodegenerative diseases by using different 0D nanomaterials.

4.1 Gold nanoparticles

Gold nanoparticles (AuNPs) have attracted great interest as a novel platform in catalysis, drug delivery, and disease diagnosis/treatment owing to their biocompatibility, intriguing optical properties, surface functionalization, and immunological properties.^{154,155} Also, due to the diverse sizes, shapes, and surface properties, AuNPs have also been constructed to treat diverse central nervous system diseases. Moreover, AuNPs have been applied to modulate AD-related A β fibrillation under intracellular/extracellular spaces.¹⁵⁶ Liao *et al.*¹⁵⁷ studied the surface charge of AuNPs by different surface functionalization modifications for effecting A β fibrillation. Interestingly, although bare and negatively charged AuNPs both could effectively inhibit A β fibrillization and disaggregate A β fibrils and spherical oligomers compared with positively charged AuNPs, the negatively charged AuNPs exhibited higher inhibition ability than bare AuNPs during A β fibrillization-reduced neurotoxicity. Moreover, the neurotoxicity decreased only when incubated with bare and negatively charged AuNPs in a concentration-dependent manner (Fig. 8A). Apart from that, Wang *et al.*¹⁵⁸ also studied the different shapes and effects of



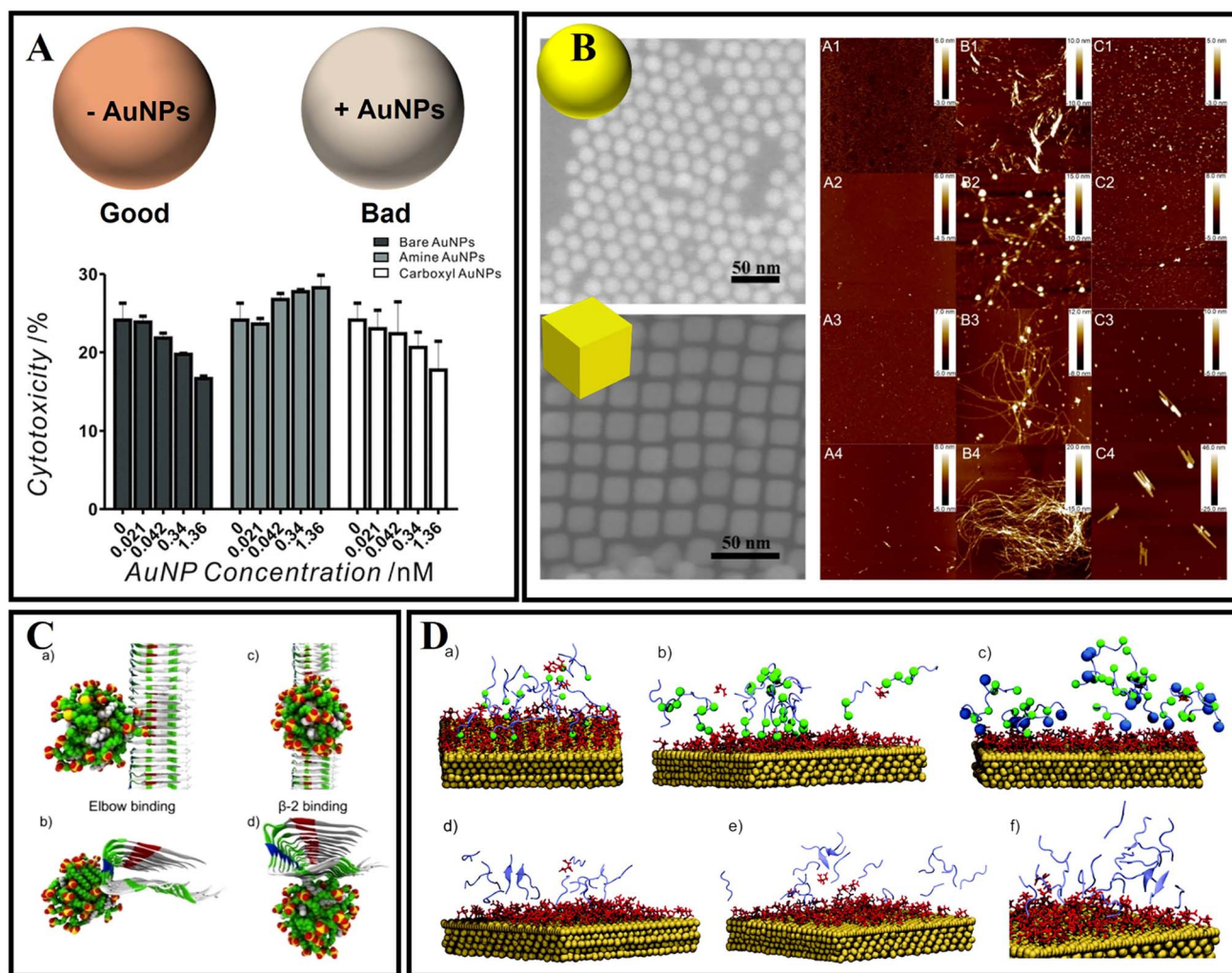


Fig. 8 (A) Cytotoxicity of the end-point products of A β fibrillization incubated with and without bare, amine-conjugated, and carboxyl-conjugated AuNPs. Bare and negatively charged AuNPs both could effectively inhibit A β fibrillization and disaggregate A β fibrils and spherical oligomers compared with positively charged AuNPs.¹⁵⁷ (B) AFM images ($5 \times 5 \mu\text{m}^2$) of the aggregates of A β_{40} (A1–4), A β_{40} and AuNS (B1–4), and A β_{40} and AuNC (C1–4) systems at different incubation times: 12 h (A1, B1, and C1), 24 h (A2, B2, and C2), 48 h (A3, B3, and C3), and 72 h (A4, B4, and C4).¹⁵⁸ (C): (a) and (b) the elbow binding of a 2 nm 70% MUS–30% OT AuNP on the protofibril; (c) and (d) the β -2 binding as seen from the top and front of the fibrils.¹⁶⁰ (D) Snapshots of MD simulations of amyloid peptides (purple) and gold surfaces (gold) covered with a citrate layer (red). (a) GNNQQNY peptide monomers bound to the gold surface. The terminal glycine (green ball) illustrated the favored N-terminal binding of the peptide to the citrate-stabilized gold nanoparticle surface. (b) NNFGAIL peptide monomers bound to the citrate-stabilized gold surface with the asparagine residues shown as green balls (N-terminus and position 2) to illustrate the N-terminal binding of the peptide. (c) VQIVYK peptide monomers (valine residues at the N-terminus and position 5 shown as green balls) at the gold surface with the C-terminal lysine (blue ball). The positively charged lysine at the C-terminus leads to binding of the peptide to the surface *via* both the N-terminus and the lysine side chain. The peptide monomers (VQIVYK) form parallel (d and e) and antiparallel (f) aligned dimers in solution and after binding to the gold surface.¹⁶¹

AuNPs on the aggregation of A β . The authors firstly prepared gold nanospheres (AuNSs) and gold nanocubes (AuNCs). The results of thioflavin T fluorescence assay showed that both AuNSs and AuNCs could inhibit A β fibrillation, but the effect efficiency of AuNSs is stronger than that of AuNCs. As shown in Fig. 8B, the shape of AuNPs influences the fibrillation kinetics of A β and the morphologies of A β fibrils. As a possible mechanism of shape-dependent AuNP–A β interactions, the authors analyzed that the surface energy of AuNPs is key for driving interaction between peptides and NPs. The AuNPs with an enormous specific surface area will inevitably adsorb peptide molecules on their surface. Compared to AuNCs, the spherical

surface produces a large density of low-coordinated atoms situated on the edges and corners of AuNSs. Therefore, AuNSs have a stronger interaction with A β than AuNCs. Coincidentally, Tapia-Arellano *et al.*¹⁵⁹ also found that the shape of the AuNPs could affect the aggregation kinetics of A β . They researched the effect of flat gold nanoprisms (AuNPr) and curved gold nanospheres (AuNSs) on A β aggregation kinetics and found that AuNPr accelerated the aggregation process and AuNSs slow down this process.

The interaction mechanism between the surface of gold nanoparticles and A β fibrils also needs to be studied with MD simulations. As shown in Fig. 8C, the AuNPs can interact with



the amino-acid sequence of $^{31}\text{HGLMVGGVV}^{41}$.¹⁶⁰ After 10 ns, the AuNPs can move along the region of the β -sheet. Amino acids including Ile31, Gly33, Met35, Gly37, Val39, and Ile41 in A β fibrils were involved in binding with AuNPs. John's group also investigated the influence of AuNPs on peptide aggregation by studying the amyloid model peptides (Fig. 8D).¹⁶¹ They designed citrate-modified AuNPs and used MD simulations to confirm the structure-forming properties of the citrate-gold surface. They found that peptide monomers presented favored N-terminal adsorption to the surface of citrate-modified AuNPs by electrostatic attraction. Based on MD simulations, it was concluded that the initial contact of charged groups with the gold surface resulted in a local elevation and alignment of peptide monomers on the surface.

Besides studying citrate-modified AuNPs, biomolecular functionalized AuNPs have also been investigated. *Scutellaria barbata* leaf extract mediated AuNPs and mimosine functionalized AuNPs have also been identified to suppress AD-related β -amyloid aggregation and neuronal toxicity.^{162,163} However, the interactions between AuNPs and A β are typically nonspecific, and thus it is a great challenge to specifically target A β by using AuNPs. In addition, most studies have only focused on the simple surface–interface interactions between A β and AuNPs, the potential function needs to be deeply tapped. Therefore, Xiong *et al.*¹⁶⁴ designed a kind of dual peptide coupled AuNPs. As one of the functional peptides, the VVIA (A β_{39-42}) fragment can specifically target A β and efficiently reduce A β -induced toxicity by generating nontoxic heterooligomers. Meanwhile, LPFFD can efficiently interact with the KLVFFAE of the central hydrophobic cluster of the A β sequence. As a result, the inhibition ability of the corresponding peptide@AuNPs against A β aggregation and cytotoxicity is greatly improved. Thereafter, the dual peptide modified AuNPs (VVIACLPFFD (VCD10)@AuNP) are the most effective in inhibiting A β oligomerization and the cytotoxicity caused by the aggregation species.

4.2 Gold nanoclusters

Unlike AuNPs, gold nanoclusters (AuNCs) with a core size below 2 nm consist of a few to several hundred Au atoms.¹⁶⁵ Thanks to their unusual properties, including strong photoluminescence, significant Stokes shift, good biocompatible, and biodegradation characteristics, AuNCs have been applied to disease-related diagnosis and treatment.¹⁶⁵ Especially as an innovative nanomedicine, AuNCs also have significant promise in amyloid-related disease applications.

As shown in Fig. 9A, Gao *et al.*¹⁶⁶ reported nanoclusters (AuNCs) for the inhibition of amyloid aggregation. The authors prepared L-glutathione stabilized AuNCs and found that AuNCs with smaller sizes could completely inhibit amyloid aggregation and efficiently prevented A β from aggregation to larger oligomers, thus avoiding nucleation to form fibrils. As shown in Fig. 9B, Shi *et al.*¹⁶⁷ designed a novel dual-responsive “cage metal chelator” release system based on AuNCs for non-invasive remote control to promote clioquinol (CQ) release and solubilize A β deposition. As a redox- and temperature-sensitive molecule, arylboronic esters were utilized to modify AuNCs

for functionalized AuNCs. Therefore, the arylboronic ester-modified AuNCs could serve as a delivery system for H₂O₂-responsive controlled release. In addition, AuNCs possess a high near-infrared absorption and can further enhance the release of chelators under NIR light. As a result, this system can effectively inhibit A β aggregation and protect neurons from A β -reduced toxicity. Moreover, the photothermal effect of AuNCs can also serve as an effective means to dissolve A β amyloid deposits. Zhang *et al.*¹⁶⁸ reported one type of Cys-Arg (CR) dipeptide modified Au nanocluster (Au₂₃(CR)₁₄) that was able to effectively dissolve pre-formed A β fibrils into monomers and recover the natural unfolded state of A β peptides from misfolded β -sheets (Fig. 9C). In addition, Au₂₃(CR)₁₄ was able to cross the BBB and cleared endogenous A β plaques in the brain of transgenic AD model mice. However, the interactions between traditional AuNCs and A β are also typically nonspecific, and thus it is also a great challenge to specifically target A β by using AuNPs. Recently, Hao *et al.*¹⁶⁹ used a peptide fragment (CLVFFA) to modify AuNCs (AuNCs-CLVFFA) and CLVFFA could target binding the central hydrophobic region LVFFA of A β (Fig. 9D). Because the LVFFA is the central hydrophobic fragment of A β and can inhibit the aggregation of A β , AuNCs-CLVFFA was able to effectively inhibit A β aggregation and prolongation and disaggregate mature fibrils. Moreover, AuNCs-CLVFFA inhibited the transformation of A β from a random coil to a β -sheet structure.

We can also imagine the future development of functionalized AuNCs for amyloid aggregation-related diseases. With the deepening of research, we expect versatile AuNCs to become an essential platform for AD research.

4.3 Metal oxide nanoparticles

Metal oxide nanoparticles such as CeO₂ NPs, ZnO NPs, CuO NPs, and Fe₃O₄ NPs have a variety of functional properties such as UV-barrier, antimicrobial, antioxidative, catalytic, and magnetic properties.^{170,171} Therefore, they have been extensively used in the field of drug delivery, disease diagnosis, disease treatment, and enzyme immobilization.¹⁷² Among them, CeO₂ NPs, ZnO NPs, and Fe₃O₄ NPs have also been researched in amyloid aggregation-related neurodegenerative disorders.

Due to their nontoxic nature, excellent biocompatibility and significant antioxidant activity at physiological pH values, cerium oxide nanoparticles (CeO₂ NPs) have been given special attention.¹⁷³ In addition, CeO₂ NPs have both superoxide dismutase (SOD) mimetic activity and catalase mimetic activity by the Ce³⁺/Ce⁴⁺ valence transition, which also provides CeO₂ NPs with an extra antioxidant function.¹⁷⁴ Recently, CeO₂ NPs have been used to protect neuron cells from A β -induced damage and treat neurocentral disease. In addition, CeO₂ NPs can cross the BBB. Therefore, CeO₂ NPs can be a promising candidate for treating AD. Recently, Li *et al.*¹⁷³ designed a novel double delivery platform, which combined the advantages of controlled-release systems with those of glucose-coated CeO₂ NPs (G-CeO₂NPs). G-CeO₂NPs could specially release the CeO₂NPs and Cu²⁺ chelators by H₂O₂ stimulation. Therefore, the G-CeO₂ NPs possess anti-aggregation properties and anti-



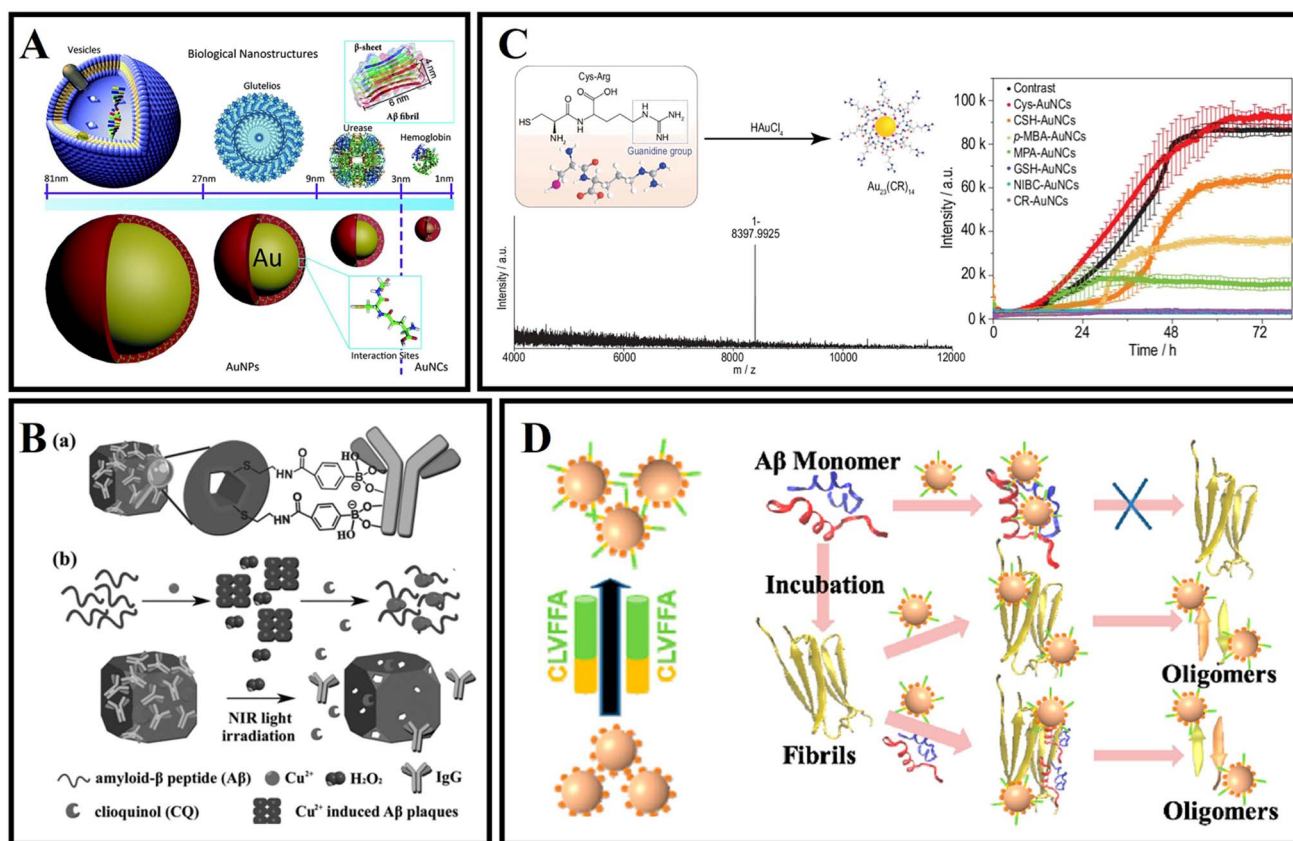


Fig. 9 (A) Biomolecule-modified AuNPs and AuNCs to simulate different size biological entities to study the size effect of bio-nanointerfaces when they interact with A β .¹⁶⁶ (B): (a) Illustration of IgG capped AuNC (AuNC-IgG). (b) H₂O₂-fueled and photothermal-responsive release of CQ from AuNC-IgG. CQ can chelate Cu²⁺ to disaggregate amyloid- β peptide (A β) plaques and inhibit H₂O₂ production.¹⁶⁷ (C) Synthesis of CR-AuNCs and characterization of CR-AuNCs by ESI-MS and fibrillation kinetics for 20 $\mu\text{mol L}^{-1}$ A β_{40} in the absence or presence of 25 mg L^{-1} Cys-AuNCs, CSH-AuNCs, *p*-MBA-AuNCs, MPA-AuNCs, GSH-AuNCs, NIBC-AuNCs or CR-AuNCs.¹⁶⁸ (D) AuNCs-CLVFFA inhibited A β_{40} aggregation and proliferation, and disaggregated mature fibrils.¹⁶⁹

oxidation properties. In addition, Li *et al.* adopted mesoporous silica nanoparticles as the carrier vehicles for loading G-CeO₂-NPs and 5-chloro-7-iodo-8-hydroxyquinoline. The research result showed that G-CeO₂NPs could effectively inhibit A β aggregation, decrease cellular ROS and protect neurons from A β -induced toxicity. Guan *et al.*¹⁷⁴ designed a bifunctional nanozyme (namely CeONP@POMs) by coating CeONP with POMs. The authors found that CeONP@POMs effectively inhibited A β aggregation, degraded A β aggregates, and reduced ROS levels. Moreover, CeONP@POMs is able to cross the BBB, regulate microglia, and protect neuronal cells from A β -related cytotoxicity. Coincidentally, a multifunctional AD therapeutic system, namely CeNP@MnMoS₄, was designed and used to maintain metal ion homeostasis, reduce oxidative stress levels, and promote cell differentiation.¹⁷⁵ Furthermore, due to the SOD activity, CeNP@MnMoS₄ can protect cells from oxidative stress. Based on the catalase and superoxide dismutase activity of CeO₂ and the hot electrons produced by gold nanorods, Ge *et al.*¹⁷⁶ designed dumbbell-shaped nanocomposites (Au-CeO₂) by coating both ends of gold nanorods with CeO₂ NPs, and endowed Au-CeO₂ with photocatalysis and photothermal effects in the NIR (Fig. 10A). To further improve

the therapeutic efficiency of Au-CeO₂, the authors used A β -targeted peptides (KLVFF) to modify Au-CeO₂ and obtained an A β -targeted nanocomposite (K-CAC). The related results exhibited that K-CAC could improve the cognitive function of AD mice.

As a type of magnetic nanoparticles (MNPs), iron oxide nanoparticles (IONs) are considered promising materials due to their high biocompatibility, unique magnetic properties, and ability to function as multimodal contrast agents.^{177,178} In addition, IONs have potential high affinity for circulating A β forms to induce a “sink effect” and potentially ameliorate AD.¹⁷⁹ Mahmoudi *et al.*¹⁷⁸ found that lower concentrations of superparamagnetic iron oxide nanoparticles (SPIONs) inhibited fibrillation, while higher concentrations increased the rate of A β fibrillation. And it was evident that the positively charged SPIONs could promote fibrillation compared with negatively charged or uncharged SPIONs. Currently, the surface functionalization of nanoparticles by using chemical methods is becoming more and more popular. Qu's group designed a multi-functional nanosystem (MNP@NFP-pep) by modifying a naphthalimide-based fluorescent probe and KLVFF peptide on the surface of magnetic nanoparticles, which can both specifically detect A β oligomers and achieve the wireless deep



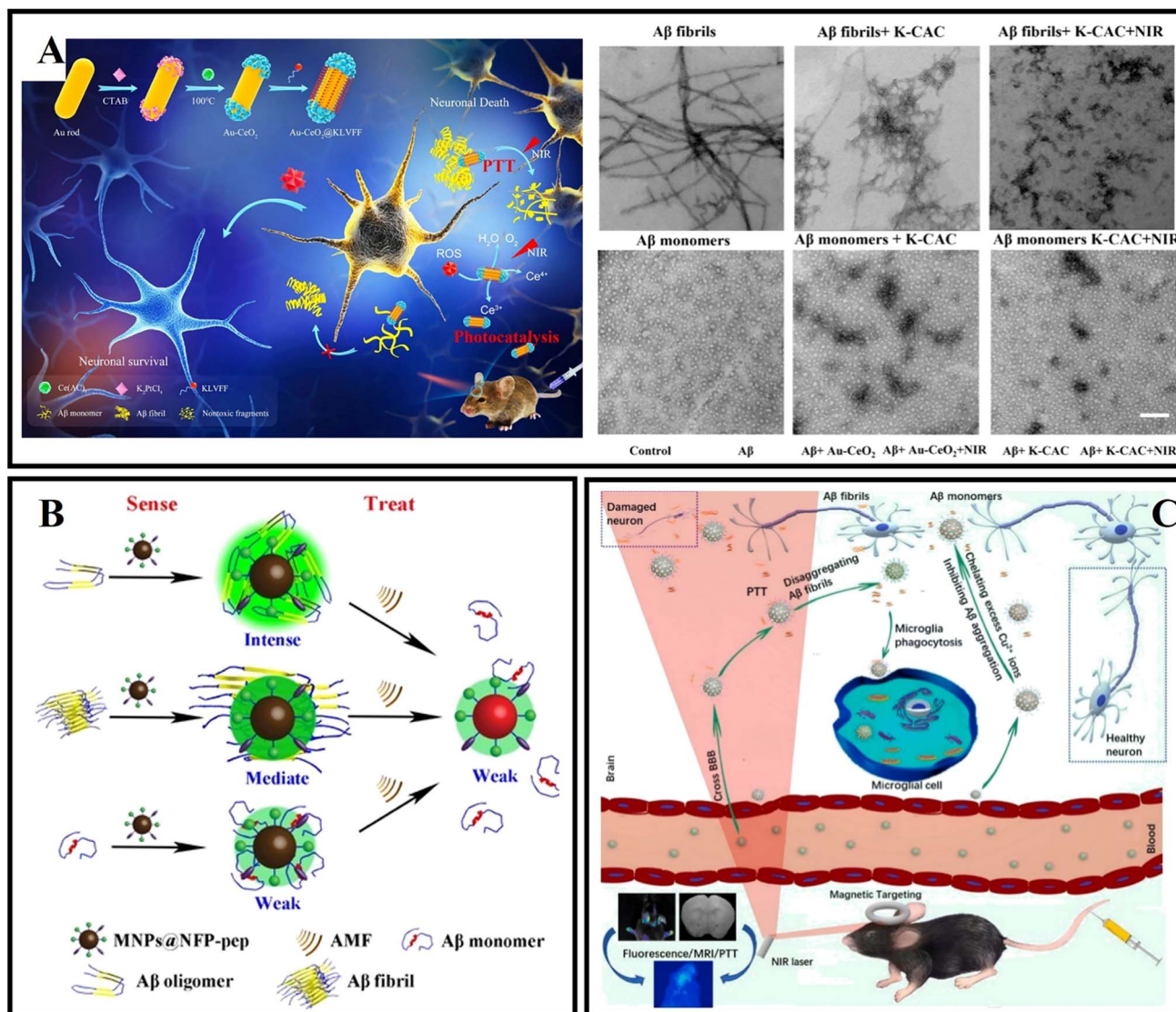


Fig. 10 (A) Au-CeO₂ exert antioxidant stress and target inhibition of Aβ through photocatalysis and the photothermal effect.¹⁷⁶ (B) MNP@NFP-pep-based "sense and treat" system.¹⁸⁰ (C) The B-FeCN nanosystem as a multifunctional nanocaptor with high BBB permeability to capture superfluous Cu ions and inhibit Aβ aggregation for magnetic targeting phototherapy.¹⁸

magnetothermally mediated disaggregation of Aβ aggregates with an alternating magnetic field.¹⁸⁰ MNP@NFP-pep can interact with the exposed hydrophobic residues of Aβ oligomers based on π - π stacking and hydrophobic interaction (Fig. 10B). MNP@NFP-pep was able to specifically target Aβ aggregates and break down Aβ aggregates. Recently, our group presented drug-based magnetic imprinted nanoparticles (MINs@EGCG) combined with epigallocatechin-3-gallate (EGCG) and magnetic nanoparticles.¹⁹ MINs@EGCG exhibited triple functions for amyloid inhibition, drug delivery and fiber separation under an external magnet. MINs@EGCG inhibited the formation of amyloid fibrils with a high efficiency for 80%. Moreover, with the help of an external magnetic field, the cleaning efficiency is up to 80%. In addition, Halevas *et al.*¹⁸¹ prepared a nanocarrier (MMSNPs) by the sol-gel method using a magnetic core of Fe₃O₄ and a mesoporous silica shell and modified the flavonoid

quercetin on the surface of MMSNPs for obtaining QCMSNPs. QCMSNPs exhibited potential anti-amyloid and antioxidant abilities. Moreover, QCMSNPs reduced Aβ-induced cellular toxicity and minimized Aβ-induced ROS generation. Recently, Dyne *et al.*¹⁸² found that mild magnetic nanoparticle hyperthermia could destroy mature Aβ fibers by local heat and facilitate the phagocytic clearance of Aβ as well as attenuating pro-inflammatory responses by microglial cells. As shown in Fig. 10C, Gong *et al.*¹⁸ reported an intelligent nanosystem (B-FeCN) by modifying carbon nitride nanodots and benzothiazole aniline on the surface of Fe₃O₄@mesoporous silica nanospheres. Among them, B-FeCN effectively traps excessed Cu²⁺ and inhibits the formation of Cu²⁺-Aβ complexes. In addition, B-FeCN generated local heat to promote the depolymerization of fiber precipitates. Interestingly, the BBB permeability of B-FeCN was significantly improved under NIR irradiation.



Thanks to the advantages of the Fe_3O_4 cores, B-FeCN entered the brain and targeted the $\text{A}\beta$ region with the help of a magnetic field. Benzothiazole aniline (BTA) makes B-FeCN a detection agent for specifically targeting $\text{A}\beta$ plaques and imaging the $\text{A}\beta$ species by fluorescence. However, B-FeCN has a certain biological toxicity, and the research on the metabolic mechanism *in vivo* is not perfect, which hinders further applications.

4.4 Organic and inorganic quantum dots

Therapeutic agents should be completely cleared from the body in a reasonable time, and usually, effective renal and hepatic clearance requires drugs less than 10 nm, and the development of nanoparticles with excellent biocompatibility is of great importance.¹⁸³

Sun *et al.*¹⁸⁴ prepared BPQDs with excellent NIR photo-thermal properties and biocompatibility using the liquid phase

exfoliation method. The size distribution of the prepared BPQDs was only 2.6 nm. BPQDs were conjugated with PEG and exhibited high stability in the physiological medium and low toxicity for different cell types. More importantly, BPQDs induced the death of C6 and MCF7 cancer cells under NIR illumination, indicating that the BPQDs have great potential as photothermal agents with implications for the treatment of amyloid-related diseases. Wang *et al.*¹⁸⁵ found that BPQDs at 100 ng mL^{-1} inhibited insulin aggregation and disaggregated mature fibers, and the inhibitory effect persisted through all stages of insulin aggregation (Fig. 11A). Molecular dynamics simulations showed that BPQDs could stabilize the α -helix structure of insulin and reduce the β -sheet content. Bu *et al.*¹⁸⁶ reported using BPQDs as a photoactive material and heme as an electron acceptor sensor to monitor the $\text{A}\beta$ protein content, and

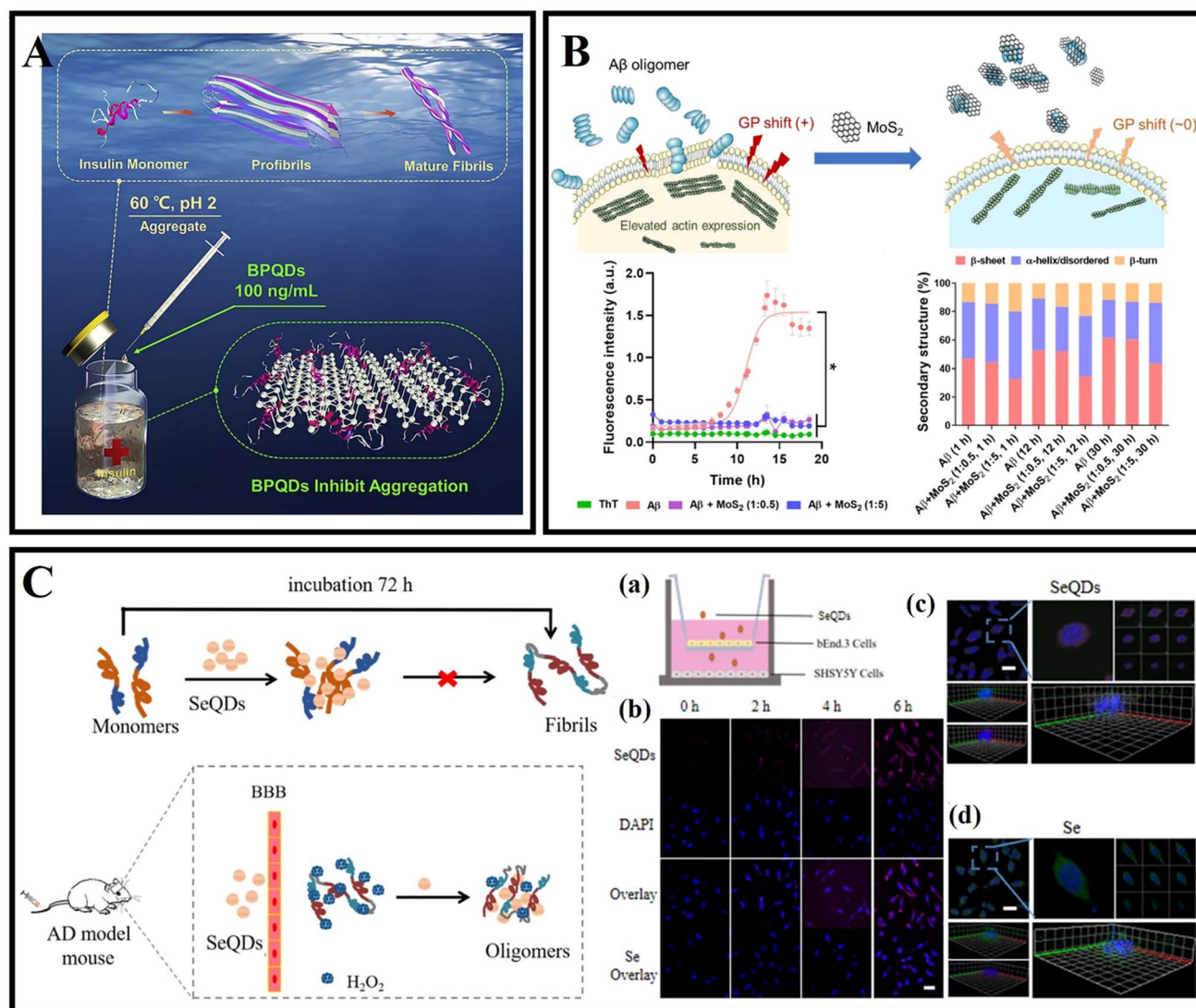


Fig. 11 (A) Amyloid aggregation of insulin in the absence and presence of BPQDs.¹⁸⁵ (B) Cell membrane disruption by $\text{A}\beta$ oligomers and its rescue by ultrasmall MoS_2 QDs. ThT fluorescence kinetic assay and attenuated total reflection (ATR)-FTIR indicated the inhibitory effects of ultrasmall MoS_2 QDs on $\text{A}\beta$.¹⁹⁰ (C) Se QDs for dissociating $\text{A}\beta$ fibrils and crossing the BBB. (a and b) Transwell experiment and cellular uptake. Scale bar, 25 μm . (c and d) 3D SH-SY5Y cell fluorescence image. Scale bar, 30 μm .¹⁹⁴



these properties make BPQDs a promising candidate for the treatment of amyloidosis and neurodegenerative disease.

Molybdenum disulfide quantum dots (MoS₂ QDs) have been widely used for live bioimaging and nanomedicine because of their low toxicity, excellent cell permeability and biocompatibility, and strong luminescence properties.^{187,188} Sun *et al.*¹⁸⁹ used a one-pot hydrothermal method to synthesize cysteamine functionalized MoS₂ QDs, which effectively inhibited the fibrillation and destabilized preformed fibrils of bovine serum albumin in a concentration-dependent manner. Li *et al.*¹⁹⁰ observed cell membrane perturbation and actin reorganization, which were induced by A β oligomers. Further research revealed that the ultra-small MoS₂ QDs restored membrane fluidity and inhibited A β amyloid aggregation (Fig. 11B). Based on the calculation of discrete molecular dynamics simulations, it was found that MoS₂ QDs were bound to the N-terminal of A β peptides through hydrophilic interactions. In addition, surface-coated A β oligomers by MoS₂ QDs could not further associate with cell membranes. Tian *et al.*¹⁹¹ pointed out the promising application of MoS₂ QDs in photodynamic therapy. MoS₂ QDs promote the creation and separation of electron-hole pairs more effectively than MoS₂ nanosheets. Therefore, MoS₂ QDs are able to generate a variety of ROS under illumination. Results related to MoS₂ QDs broaden the application of molybdenum disulfide-based nanomaterials.

As drugs or nanocarriers, selenium nanoparticles have made important progress in cancer, AD and other diseases because of their excellent physicochemical characteristics.¹⁹² It has been reported that selenium nanoparticles have a high affinity for A β ,

which can inhibit A β aggregation and treat AD as a potential nanomedicine.¹⁹³ As shown in Fig. 11C, Guo *et al.*¹⁹⁴ synthesized selenium quantum dots (Se QDs), which could quickly penetrate the BBB because of their ultrasmall size and excellent biocompatibility. Se QDs had a strong free-radical scavenging activity and could protect cells from oxidative stress damage. Se QDs could not only inhibit A β aggregation and reduce A β -mediated cytotoxicity, but also effectively reduce tau protein phosphorylation, further improve oxidative stress, and maintain nerve cell stability. In conclusion, Se QDs had great advantages compared with traditional single-target drugs in the treatment of AD.

4.5 Carbon-based zero-dimensional nanomaterials

Carbon nanomaterials are widely used to inhibit A β aggregation due to the various surface and interface interactions between the A β peptide and carbon nanomaterials.³⁴ Carbon dots (CDs), as a new type of carbon-based zero-dimensional nanomaterial, have attracted extensive research in recent years because of their low cost, easy synthesis, good biocompatibility, photoluminescence, easy surface modification, and high stability.¹⁹⁵ It's important to note that CDs include graphene quantum dots (GQDs), carbide polymer dots (CPDs), and carbon quantum dots (CQDs).¹⁹⁶

GQDs are single- or few-layered graphene sheets of 10 nm or less in size.¹⁹⁷ Most CDs possess size-dependent auto-fluorescence originating from quantum confinement and edge effects, compared with carbon nanotubes, fullerenes, and graphene nanomaterials.¹⁹⁸ According to previous studies, GQDs

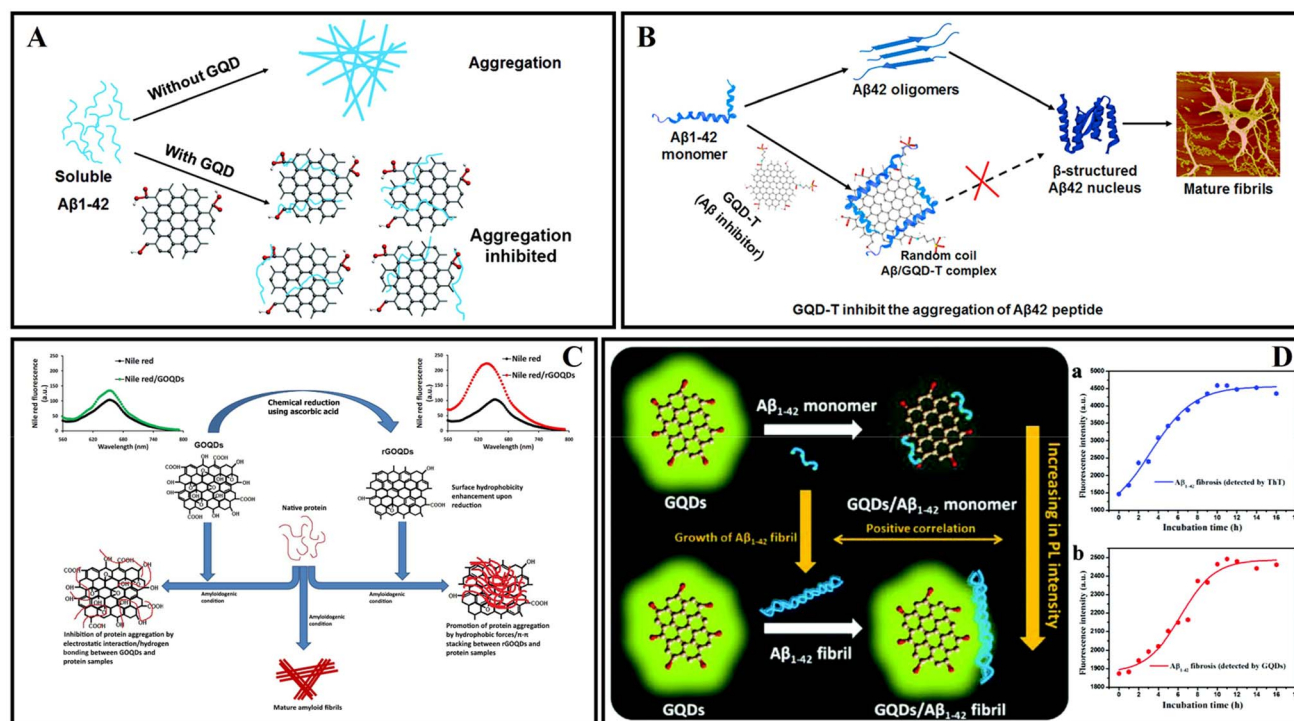


Fig. 12 (A) The GQDs used for inhibiting the aggregation of A β ₄₂ peptides.¹⁹⁹ (B) GQD-T inhibits the aggregation of A β ₄₂ peptides.²⁰³ (C) GOQDs have the capacity to inhibit the fibrillation of protein.²⁰⁸ (D) Proposed mechanism for the different fluorescence behaviors of GQDs on A β ₄₂ monomers and fibrils.²⁰⁹



have a good ability to cross the BBB, effectively modulate the A β aggregation process and reduce A β -induced neurotoxicity.⁹⁵ Therefore, GQDs are often combined with A β aggregation inhibitors or neuroprotective peptides to enhance efficacy. In 2015, Liu *et al.*¹⁹⁹ prepared GQDs by a hydrothermal method, demonstrating that GQDs effectively inhibited A β_{42} peptide aggregation (Fig. 12A). Moreover, Xiao *et al.*²⁰⁰ prepared a novel nanomaterial GQDG by conjugating GQDs with glycine-proline-glutamate (Gly-Pro-Glu). *In vitro* assays proved that both GQDs and GQDG could inhibit the aggregation of A β_{42} . *In vivo* assays indicated that GQDG enhanced AD model mice's learning and memory capacity, increased dendritic spine amounts, and decreased several pro-inflammatory cytokine content. Subsequently, several studies reported the application of nitrogen-doped graphene quantum dots (N-GQDs) and fluorine-functionalized graphene quantum dots (FGQDs) in amyloid aggregation.^{201,202} Liu *et al.*²⁰³ covalently combined GQDs with tramiprosate to design a novel A β aggregation inhibitor, namely GQD-T. GQD-T showed the capability of inhibiting A β aggregation and rescuing A β -induced cytotoxicity due to the synergistic effect of the GQDs and tramiprosate (Fig. 12B). Moreover, GQDs can effectively disperse mature amyloid-rich *Staphylococcus aureus* biofilms and interfere with the self-assembly of amyloid fibers.²⁰⁴ Liu *et al.*²⁰⁵ studied the regulatory effects and mechanism of GQDs on A β_{42} aggregation and found that electrostatic interaction was the major driving force in the co-assembly process of A β_{42} and GQDs. Tak *et al.*²⁰⁶ used *Clitoria ternatea* as a precursor with the help of a one-pot microwave-assisted method to prepare novel graphene quantum dots ctGQDs. The transport efficiency of ctGQDs across the BBB was increased significantly and showed high inhibition efficiency of the acetyl cholinesterase enzyme. Meanwhile, Perini *et al.*²⁰⁷ reviewed the potential of GQDs in biomedicine and neuroscience and discussed the ability of GQDs to cross the BBB and reach the brain. Ghareghozloo *et al.*²⁰⁸ studied the inhibiting effect of graphene oxide quantum dots (GOQDs) on bovine insulin and hen egg white lysozyme (HEWL) aggregation. GOQDs were prepared through pyrolysis of citric acid, and the reduction step was carried out using ascorbic acid. The results showed that GOQDs could inhibit the related protein fibrillation, and the presence of reduced GOQDs was found to promote protein assembly *via* shortening the nucleation phase. The content of oxygen-containing functional groups from the GOQD surface may be the key factor in affecting fibrillation (Fig. 12C).

The detection of the concentration of amyloid monomer is of great importance in diagnosing AD. Huang *et al.*²⁰⁹ proposed a method to detect A β monomer concentration using the fluorescent properties of GQDs (Fig. 12D). The positively charged groups, the aromatic structure and moieties with hydrogen bonding ability on A β_{42} monomers provided suitable conditions for the interaction between A β_{42} monomers and GQDs. This strong combination promoted the excited-state electron transfer from GQDs to A β_{42} , resulting in quenching of the PL intensity of GQDs. The A β fibers consume abundant interaction sites and contact surface areas through a self-assembly process, and the interaction between A β fibers and GQDs is much

weaker to quench GQD fluorescence. Yousaf *et al.*²¹⁰ reported the detection of monomers and oligomers using specific fluorescence and a magnetic resonance imaging (MRI) multimodal probe based on bovine-serum-albumin-capped fluorine functionalized GQDs (BSA@FGQDs). BSA@FGQDs could monitor amyloid fibrillation and was more sensitive than conventional ThT stain. Monitoring amyloid aggregation dynamics and monomers/oligomers using BSA@FGQD probes is based on hydrophobic, electrostatic, hydrogen bonding, and π - π stacking interactions. Tang *et al.*²¹¹ examined the influences of GQDs on the obstruction of the membrane axis of A β in its three forms of monomers (A β -m), oligomers (A β -o), and amyloid fibrils (A β -f), and demonstrated the mitigation potential of GQDs in reverting SH-SY5Y cells to their native fluidic state. It was found that A β -m is bound to the GQDs *via* strong electrostatic and hydrophobic interactions. The nanostructures reshaped the potential of mean force (PMF) of A β -o to inhibit the β -sheet propensity of the peptide residues, and GQDs adhered to the sides and ends of an A β -f, thereby hindering their elongation.

CQDs are a new class of 0D carbonaceous nanomaterials with a diameter less than 10 nm.²¹² CQDs can be produced using diverse bioorganic compounds through solvent-free pyrolysis, hydrothermal treatment, or microwave treatment. These treatment methods and bioorganic compounds allow for the synthetic flexibility of CQDs without intricate set-ups.²¹³ CQDs have outstanding features such as low cost, easy synthesis, excellent biocompatibility, and photoluminescence.²¹² The absorption and emission spectra of CQDs can be tuned by adjusting the precursor type, preparation method, degree of carbonization, surface state, and element doping.²¹⁴ In addition, CQDs have abundant functional groups, such as hydroxyl, amino, and carboxyl groups, which are easy to modify.²¹⁵ Moreover, CQDs can interact with A β peptides and aggregates through electrostatic, hydrogen bonding, π - π stacking, and hydrophobic interactions.^{15,216}

Many studies have reported the inhibition of human insulin fibrosis by using carbon dots.^{217,218} Malishev *et al.*²¹⁹ prepared enantiomeric carbon dots (L-Lys-C-dots and D-Lys-C-dots) using L-lysine or D-lysine. The results demonstrated that L-Lys-C-dots exhibited higher affinity to A β_{42} (either monomeric and/or pre-fibrillar species) compared with D-Lys-C-dots, modulated the fibril assembly process of A β_{42} (Fig. 13A). The authors speculated that the different properties of L-Lys-C-dots and D-Lys-C-dots were caused by residual lysine moieties which exposed to the C-dots' surface and residual lysine possibly interfered with the electrostatic interactions of the peptide. Zhou *et al.*¹⁵ used *o*-phenylenediamine and citric acid as precursors to synthesize amphiphilic yellow-emissive CDs (Y-CDs) by an ultrasonication-mediated methodology. The amphiphilicity of Y-CDs didn't change with different coatings. In addition, it was proved that Y-CDs could cross the BBB of zebrafish *via* passive diffusion. The related research suggested that Y-CDs could inhibit the overexpression of APP and A β peptides. Koppel *et al.*²²⁰ used brown coal to prepare novel CQDs. CQDs were able to inhibit IAPP and A β aggregation induced by lipopolysaccharide (LPS) through hydrogen bonding and hydrophobic interactions. This study contributed to



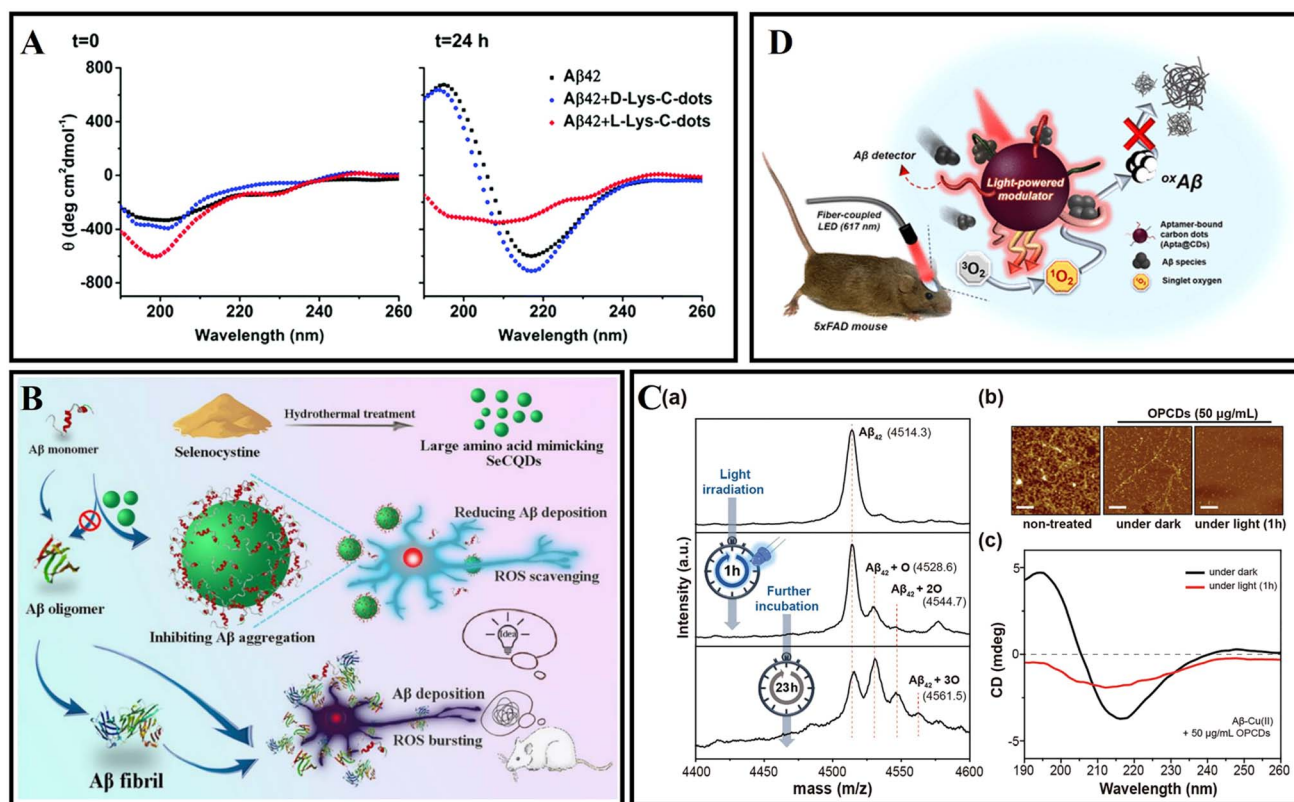


Fig. 13 (A) Secondary structures of 25 mM Aβ₄₂ monitored by CD spectroscopy in the absence or presence of D-Lys-C-dots or L-Lys-C-dots.²¹⁹ (B) Synthesis of SeCQDs and the inhibition effects of SeCQDs on Aβ aggregation and ROS production.²²¹ (C): (a) The mass spectra of Aβ-Cu(II) aggregates incubated with OPCDs for 24 hours at 37 °C. Light was irradiated only for one hour. (b) AFM images and (c) CD spectra of Aβ-Cu(II) aggregates incubated with OPCDs under dark and one-hour-light illuminating conditions.²³² (D) Aβ-targeting, CD-mediated photodynamic modulation for spatiotemporal inhibition of Aβ aggregation *in vivo*.²²⁹

understanding the pathological link between bacterial metabolites and amyloid diseases. Due to the excellent antioxidant capacity of selenium nanoparticles, Zhou *et al.*²²¹ designed selenium-doped carbon quantum dots (Se-CQDs) *via* a simple hydrothermal treatment of selenocystine, which were successfully applied to inhibit Aβ aggregation and scavenge the redundant ROS in the brain (Fig. 13B). Se-CQDs maintained the intrinsic properties of both selenium and CQDs. Se-CQDs have paired α-carboxyl and amino groups at their edges, which trigger multivalent interactions with Aβ. Li *et al.*²²² fabricated Se-CQDs using selenocystine through hydrothermal treatment under mild conditions. ROS could be effectively scavenged by the Se-CQDs. Once Se-CQDs are internalized into cells, high levels of ROS in cells are reduced. These properties enable Se-CQDs to protect biological systems from oxidative stress. Guerrero *et al.*²²³ used Na-citrate as a precursor to prepare CQDs. Pulse-chase lysozyme fibril-forming assay and ThT fluorescence showed that CQDs prevented the monomers and oligomers into mature fibrils, while could provoke the disaggregation of mature HEWL fibrils. Li *et al.*²²⁴ fabricated ultra-small CQDs with a uniform size by pulsed laser ablation. Results demonstrated that CQDs could efficiently inhibit Aβ₄₂ aggregation. Moreover, the quenching of tyrosine and ANS fluorescence of the Aβ₄₂ solutions with CQDs indicated that

there existed an interaction between the CQDs and Aβ₄₂ peptides. Our group prepared glycosylated carbon dots (g-CDs) using glucose as a precursor. gCDs-E has been prepared by self-assembly of gCDs and epigallocatechin-3-gallate (EGCG). gCDs-E could not only suppress the fibrillation of Aβ and disaggregate Aβ fibrils, but also effectively inhibit the activity of *Candida albicans*.¹³ In addition, the capability of gCDs-E for BBB penetration was also observed using a normal mice model.

As a highly active substance, ROS can be used as a disease treatment agent.²²⁵ At present, there are many research studies about photodynamic therapy for tumor diseases.²²⁶ In addition, photodynamic therapy also has good application potential in amyloid-related diseases.²²⁷ The band-to-band transition of CDs' electron carriers generates ROS through an electron- (type I) or energy-transfer (type II) process, mediating photo-modulation to denature target biotoxins.^{228,229} Like a type II photosensitizer, CQDs can react with oxygen after absorbing energy, promote the production of singlet oxygen, and oxidize the amino acid residues of Aβ peptides, thereby destroying the interaction between peptides.²³⁰

For example, Chung *et al.*²³¹ synthesized CDs using ammonium citrate through one-pot hydrothermal treatment and obtained branched polyethylenimine modified CDs (bPEI@CDs) by passivating the surface of the prepared CDs using branched



Table 2 A list of carbon-based zero-dimensional nanomaterials with the modulation mechanism and effect of amyloid aggregation

Nanomaterials	Modulation mechanisms	Effects	Ref.
GQDs	Adsorption/hydrophobic interactions	Inhibition	199
GQDG	Adsorption	Inhibition	200
FGQDs	Adsorption	Inhibition/disaggregation	201
GQD-T	Adsorption/synergistic	Inhibition	203
ctGQDs	Inhibition acetyl cholinesterase enzyme	Treating disorganization of cells	206
GOQDs	Adsorption/hydrophobic interactions	Inhibition	208
BSA@FGQDs	Hydrophobic/electrostatic/H-bonded/ π - π stacking interactions	Monitor	210
L-Lys-C-dots	Electrostatic interactions	Modulation	219
Y-CDs	Amphiphilic	Inhibiting overexpression of APP and A β peptides	15
CQDs	H-Bonded/hydrophobic interactions	Inhibition	220
Se-CQDs	Adsorption/hydrophobic interactions/anti-oxidation	Inhibiting A β aggregation and scavenging ROS	221
Se-CQDs	Anti-oxidation	Scavenging ROS	222
gCDs-E	Hydrophobic interactions/anti-oxidation	Suppressing fibrillation/ disaggregation/inhibition fungi	13
bPEI@CDs	Electrostatic interactions/photooxygenation	Inhibition/disaggregation	231
OPCDs	Chelation/hydrophobic interactions/photooxygenation	Inhibition	232
Apta@CDs	Photooxygenation/target	Inhibition	229
CPDs	Electrostatic interactions/hydrogen bonds/hydrophobic interactions	Inhibition/disaggregation	233
C ₆₀	Hydrophobic interactions	Inhibition	234
UCNP@C ₆₀ -pep	Photooxygenation/anti-oxidation	Inhibition/scavenging ROS	236

polyethylenimine. bPEI@CDs exhibited hydrophilic and cationic surface properties, which could effectively interact with negatively charged residues of A β peptides. Under light illumination, bPEI@CDs displayed a strong effect on A β aggregation and on the disaggregation of fibrils by generating ROS. Building on previous work, Chung *et al.*²³² prepared multifunctional carbon-dots (OPCDs) using *o*-phenylenediamine. The N-containing polyaromatic surface of OPCDs is the reason why the self-assembly of Cu(II)-A β is hindered, thereby weakening Cu(II) catalyzed oxidative stress and A β aggregation propensity. Illumination treatment further enhanced the inhibitory effect of OPCDs, which produced ROS to oxidize the key residues (His and Met) of A β (Fig. 13C). Recently, Chung *et al.*²²⁹ designed A β -targeted, red light-responsive apta@CD based on previous work, which inhibited A β aggregation in space and time and reduced the overall A β burden in the brain. Under red light, apta@CDs effectively inhibited the formation of A β aggregates by oxidizing A β residues, exhibiting a light-modulating effect on A β aggregation (Fig. 13D). The application of apta@CDs to 5xFAD mice further demonstrated the anti-amyloid aggregation ability of apta@CDs *in vivo*.

CPDs have also been reported for AD diagnosis and treatment. Gao *et al.*²³³ prepared multifunctional nitrogen-doped CPDs by using *o*-phenylenediamine for targeting A β aggregations. CPDs inhibited A β fibrillation and disaggregated A β fibrils through electrostatic interactions, hydrogen bonds, and hydrophobic interactions. CPDs could emit enhanced red fluorescence upon interaction with A β fibrils, clear amyloid plaques *in vivo* and prolong the lifespan of CL2006 strain by alleviating A β -induced toxicity. C₆₀ has been demonstrated to interact and prevent A β fibrillation. However, there are significant problems such as low solubility and toxicity that need to be solved.

Fullerenes and their derivatives have been reported for use in amyloid diseases. Melchor *et al.*²³⁴ synthesized diethyl fullerenemalonates and the corresponding sodium salts using the Bingel reaction, adducts of C₆₀ bearing 1 to 3 diethyl malonyl and disodium malonyl substituents (C_{60+n}(COOR)_{2n}, where *n* = 1–3 and R = –CH₂CH₃, –Na). The inhibition efficiency of bisadduct salts (C₆₂(COONa)₄) and trisadduct (C₆₃(COONa)₆) is 98% and 83% respectively. The 6.7 mM C₆₂(COONa)₄ mixture has been confirmed the capacities for anti-amyloid deposition. The anti-aggregation effect of C₆₂(COONa)₄ is mainly attributed to the hydrophobic surface and the number of substituents bound on the surface of fullerene. C₆₀ acts as both a ROS producer under UV-visible light and a ROS scavenger in the dark.²³⁵ Du *et al.*²³⁶ designed UCNP@C₆₀-pep nanoparticles, which generated ROS under NIR light and oxidized A β . Moreover, UCNP@C₆₀-pep could also alleviate the excessive ROS in the organization. Both the ROS generation and ROS quenching abilities of UCNP@C₆₀-pep were beneficial to reduce A β -induced neurotoxicity. Bobylev *et al.*²³⁷ studied the ability of water-soluble fullerene derivatives with different types of solubilizing addends for anti-amyloid aggregation. The three derivatives were found to exhibit strong anti-amyloid effects *in vitro* and low cytotoxicity *in vivo*. The fullerene derivatives have a strong anti-amyloid effect and low toxicity. Their ability for crossing the BBB and the inhibition ability of amyloid fibrillation make fullerenes potential drug candidates. Table 2 lists the mechanism and effect of carbon-based zero-dimensional nanomaterials on the modulation of amyloid aggregation.

5 Others

In addition, other nanoparticles have also been reported for diagnosis and treatment of AD, including metal-organic



frameworks (MOFs), polyoxometalates (POMs), liposomes, SiO₂, upconverting nanoparticles and so on.^{238–241}

5.1 Metal–organic frameworks

Metal–organic frameworks (MOFs) are crystalline entities composed of metal ions or clusters and polydentate organic ligands.²⁴² As an emerging family of hybrid nanomaterials, MOFs have attracted much attention due to their porous structures, good biocompatibility, and tunable sizes, and are widely used in catalytic, sensing and biological applications.^{243–246}

Wang *et al.*²³⁸ prepared NIR responsive nanoparticles PCN-224 for inhibiting A β aggregation. PCN-224 was hydrothermally synthesized by coordinating tetrakis(4-carboxyphenyl) porphyrin (TCPP) ligands with zirconium (Fig. 14A). Under NIR irradiation, PCN-224 significantly reduced A β induced cytotoxicity. The functional porphyrin linkers are separated by Zr clusters in the MOF framework, which could avoid the self-quenching of excited states, maintain the photo-oxidative properties of the porphyrin linkers, and improve the ¹O₂ generation capacity. Yu *et al.*²⁴⁷ selected four kinds of POMFs

(Zr-MOF, Al-MOF, Ni-MOF, and Hf-MOF) for further investigation, which are stable under physiological conditions and exhibit excellent biocompatibility (Fig. 14B). It was found that Hf-MOF was the most efficient A β photooxidant based on the experimental results and DFT calculations. LPFFD modified Hf-MOFs not only effectively targeted A β peptides and reduced A β -induced cytotoxicity, but also improved photooxidation in complicated environments. Yan *et al.*²⁴⁸ synthesized a core-shell nanocomposite CeONP-Res-PCM@ZIF-8/PDA/Apt through an *in situ* encapsulation strategy. Resveratrol (Res), ceria nanoparticles (CeONPs) and PCM (tetradecanol) were embedded in a ZIF-8/PDA matrix by a water-based mild method (Fig. 14C). These nanocomposites can be activated to release the encapsulated Res upon NIR illumination through PCM regulation. Moreover, CeONP-Res-PCM@ZIF-8/PDA/Apt nanocomposites exhibited multifunctional effects on inhibiting A β aggregation, disaggregating A β fibrils, and decreasing A β -induced oxidative stress and neural apoptosis. The therapeutic effect of nanocomposites could be enhanced under NIR irradiation because of the excellent photothermal properties of PDA. In 2021, Zeng *et al.*²⁴⁹ built an electron-deficient MOF from the ligand of

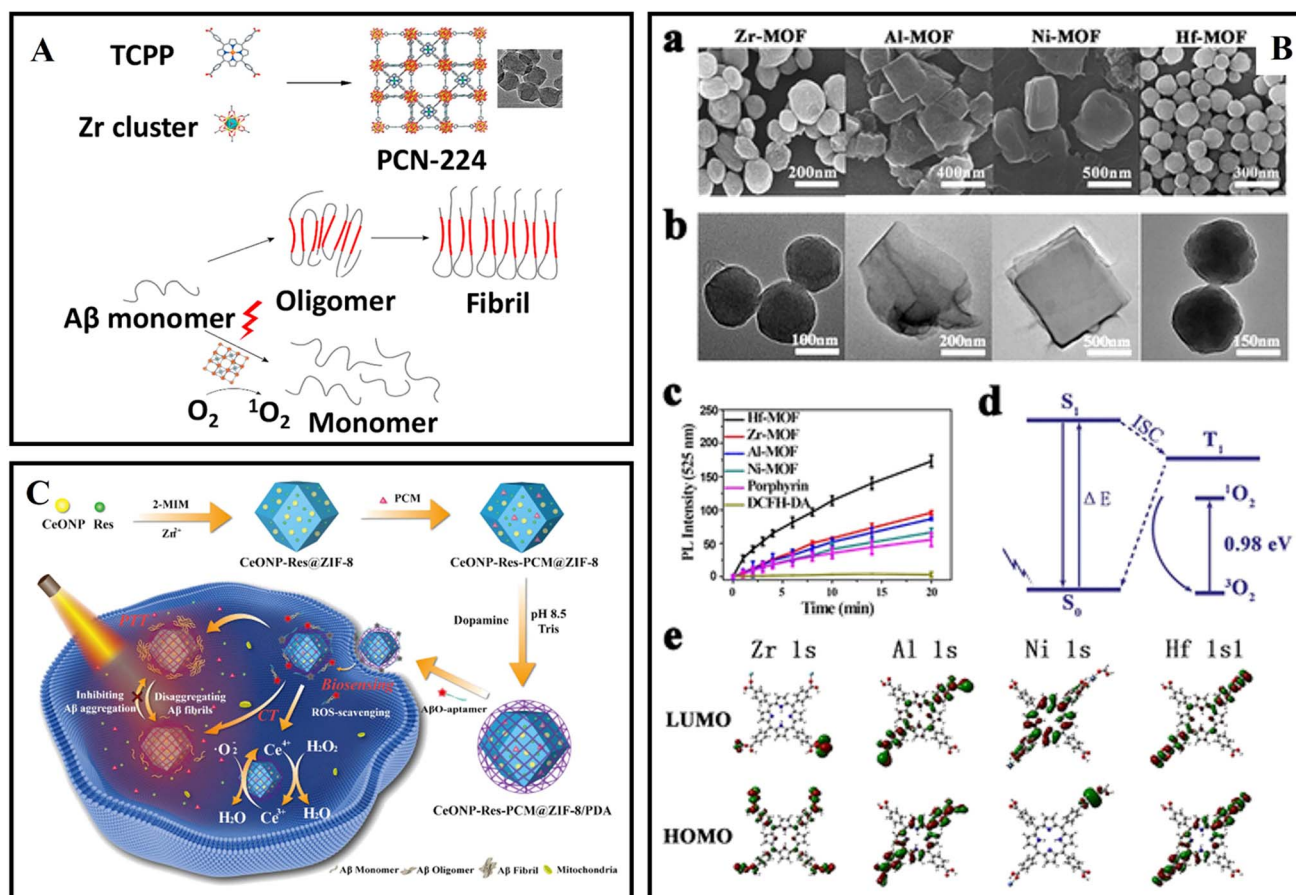


Fig. 14 (A) The synthesis of PCN-224 nanoparticles and photo-inhibition of A β ₄₂ aggregation by using PCN-224 nanoparticles.²³⁸ (B): (a) SEM images. (b) TEM images of Zr-MOF, Al-MOF, Ni-MOF, and Hf-MOF, respectively. (c) Fluorescence intensity of DCF after photooxidation by using PMOFs at different time points. (d) Jablonski diagram describing the underlying photophysics and photochemistry of photodynamic therapy. (e) Electronic density contours for the frontier molecular orbitals of the four kinds of PMOFs.²⁴⁷ (C) CeONP-Res-PCM@ZIF-8/PDA preparation and its applications in A β oligomer sensing and treatment.²⁴⁸

naphthalene diimide (NDI) and metal nodes of biocompatible Ca^{2+} . Then pyrene as an electron donor molecule was encapsulated to form a host-guest MOF self-assembled co-crystal Py@Ca-NDI . A concomitant superior charge transfer interaction between pyrene and NDI could be attained and the photothermal conversion efficiency of Py@Ca-NDI in aqueous solution could reach up to 41.8%. The treatment of neurodegenerative disease by using MOF-based materials is a challenging study, and more elaborative studies on biostability, biocompatibility and BBB penetration are still needed.²⁵⁰

5.2 Polyoxometalates

Polyoxometalates (POMs) are a special group of inorganic redox-active materials consisting of multiple metal oxide ions linked together by oxygen atoms to form nanoclusters within an ordered three-dimensional framework.²⁵¹ Due to the tunable structures, excellent physicochemical properties and good biocompatibility of POMs, many researchers have explored their application in biomedicine. POMs can act as $\text{A}\beta$ aggregation inhibitors and can be seen as candidates for the treatment of AD because of their similarity to water-soluble fullerene derivatives.²⁵²

In 2011, Qu's group reported the inhibitory effect of POMs on $\text{A}\beta$ aggregation and found that POMs with a Wells-Dawson structure had a better effect.²³⁹ Then Li *et al.*²⁵³ reported that POMs could not only inhibit $\text{A}\beta$ aggregation but also photodegrade $\text{A}\beta$ aggregates, such as $\text{A}\beta$ oligomers. Meanwhile, Li *et al.*²⁵⁴ designed bifunctional nanoparticles POM@P through the self-assembly of $\text{A}\beta_{15-20}$ peptides and POM (Fig. 15A). The aggregation process of $\text{A}\beta$ was researched by monitoring the fluorescence of Congo red's after adding POM@P . Moreover, the prepared POM@P could effectively target amyloid aggregation in mouse cerebrospinal fluid. The interaction between POMs and $\text{A}\beta$ species relies on an electrostatic effect. Gao *et al.*²⁵⁵ designed a variety of transition-metal-substituted POMds that had better inhibition efficiency of $\text{A}\beta$ aggregation than POMs. Results demonstrated that POMds with histidine-binding sites could not only specifically target the polypeptide sequence (HHQK) of $\text{A}\beta$, but also show stronger inhibitory effects through enhancing binding affinity between $\text{A}\beta$ and POMds (Fig. 15B). POMds-Dawson-Ni and POMds-Dawson-Co exhibited better effects for decreasing $\text{A}\beta$ -haem peroxidase-like activity. In addition, POMds could cross the BBB and were metabolized completely after 48 hours. Then Gao continuously designed artificial enzymes AuNPs@POMD-8pep that exhibited protease activities, SOD-like functionality, and metal-ion chelation capabilities (Fig. 15C).²⁵⁶ AuNPs facilitated electron transfer and served as a scaffold to create a coupled POMD-peptide compound.

$\text{A}\beta$ fibrils and ROS are closely related to AD pathogenesis. The reduced POMs (rPOMs) had a strong NIR absorption and ability for anti-oxidant activity.²⁵⁷⁻²⁵⁹ Ma *et al.* designed a NIR-responsive rPOM-based agent $\text{rPOMs@MSNs@copolymer}$ that consists of mesoporous silica nanoparticles (MSNs), rPOMs, and thermal responsive copolymer poly(*N*-isopropylacrylamide-co-acrylamide).²⁵² The copolymer could melt under 808 nm

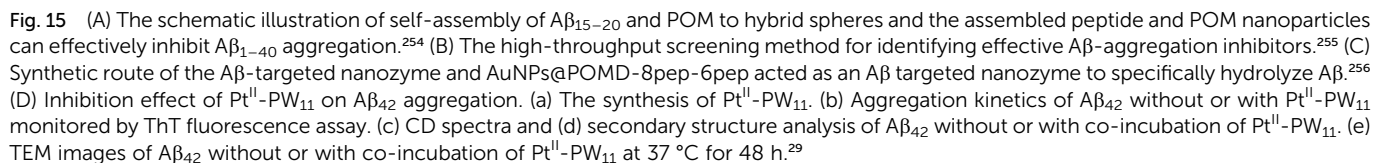
irradiation and led to the release of rPOMs. Therefore, preformed $\text{A}\beta$ fibrils could be disaggregated by local heat. Zhao *et al.* reported an organic platinum-substituted POM with a Kegging structure $(\text{Me}_4\text{N})_3[\text{PW}_{11}\text{O}_{40}(\text{SiC}_3\text{H}_6\text{NH}_2)_2\text{PtCl}_2]$ (abbreviated as $\text{Pt}^{\text{II}}\text{-PW}_{11}$) (Fig. 15D).²⁹ The negatively charged $\text{Pt}^{\text{II}}\text{-PW}_{11}$ anions could bind to the cationic cluster (HHQK) of $\text{A}\beta$ through electrostatic interaction, and $\text{Pt}^{\text{II}}\text{-PW}_{11}$ interacted with other residues through van der Waals force, hydrogen bonding and desolvation energy. $\text{Pt}^{\text{II}}\text{-PW}_{11}$ also reduced $\text{A}\beta_{42}$ aggregation-induced cytotoxicity. When the dosage reached 8 μM , cell viability increased from 49% to 67%. In 2022, Gao innovatively combined post-translational modification (PTM) technology with POMs, rationally designed and synthesized a Wells-Dawson POM-based PTM agent POMD-TZ (thiazolidine as TZ) for chemical modification of amyloid peptides.²⁶⁰ POMD-TZ could selectively bind to the Lys16 site, inhibit $\text{A}\beta$ aggregation, and reduce the cytotoxicity caused by the $\text{A}\beta$ peptide.

5.3 Liposomes

Liposomes have the advantages of non-toxicity, strong drug-carrying capacity, and ease of synthesis and modification, and have been widely used in the field of drug delivery.^{261,262}

Gobbi *et al.*²⁶³ reported that nanoliposomes containing phosphatidic acid (PA) and cardiolipin (CL) targeted aggregated forms of $\text{A}\beta_{42}$ fibrils (22–60 nm) with high binding affinity. Mourtas *et al.*²⁴⁰ successfully used click chemistry to decorate the surface of nanoliposomes with curcumin, and the curcumin-modified liposomes (maintaining the planarity) had extremely high affinity for $\text{A}\beta_{42}$ fibers (1–5 nm) and had sufficient stability for *in vivo* applications. This high-affinity binding may be due to a multivalent interaction between click curcumin liposomes and $\text{A}\beta$. Taylor *et al.*²⁶⁴ designed and formulated different types of nanosized liposomes incorporating or decorated with curcumin, a curcumin derivative, or lipid ligands (PA, CL, or GM1 ganglioside), and then evaluated their ability to influence $\text{A}\beta_{42}$ peptide aggregation based on ThT and a sandwich immunoassay. The results showed that the click-curcumin type was by far the most effective. Bana *et al.*²⁶⁵ prepared phosphatidic acid and ApoE-derived peptide bi-functionalized mApoE-PA-LIP . mApoE-PA-LIP strongly bound the $\text{A}\beta$ peptide ($K_D = 0.6 \mu\text{M}$), inhibited peptide aggregation and triggered preformed aggregates. The permeation rate across the BBB of mApoE-PA-LIP was 5-fold higher with respect to monofunctional liposomes. Papadia *et al.*²⁶⁶ developed multifunctional LUV liposomes (mf-LIPs) having three ligands, one of which is a curcumin-lipid ligand (TREG) and the other two ligands target the transferrin and the LDL receptors of the BBB. Further research found that the multiple ligands of mf-LIPs did not interfere with each other, and mf-LIPs have multiple functions such as targeting the BBB and inhibiting amyloid aggregation. Meanwhile, *in vivo* experiments found that the curcumin ligand increases the stealth properties of liposomes by reducing their uptake by the liver and spleen.²⁶⁷ Kuo *et al.*²⁶⁸ designed a drug carrier system of ApoE-modified liposomes conjugated with PA. This system was used to improve BBB





biocompatibility and low toxicity attributed to their metal-free nature, thus being an excellent candidate for drug delivery and biological applications.²⁷³ Zhang *et al.* designed a two-photon NIR-II-activated photooxygenation catalyst DSM@*n*-HOF-6 (DSM = 4-[*p*-(dimethylamino) styryl]-1-methylpyridinium). TCPP(*meso*-tetrakis(carboxy phenyl) porphyrin) was periodically incorporated into HOFs, while the targeting peptide KLVFFAED (KD8) was conjugated to DSM@*n*-HOF-6 (DSM@*n*-HOF-6@KD8).²⁷⁴ The up-conversion fluorescence of DSM could be absorbed by TCPP to generate ¹O₂ for Aβ oxygenation, and DSM@*n*-HOF-6@KD8 could inhibit the fibrillation of Aβ monomers and reduce the cytotoxicity of Aβ by photooxygenation. The application of polystyrene nanoparticles and upconverting nanoparticles in amyloid diseases has also been reported.^{275,276}

Many nanomaterials have been reported for AD diagnosis and treatment. Targeting issues and the interaction between nanomaterials and peptides are the main issues that need to be considered. At the same time, issues such as inhibition efficiency, reversibility of fibrosis, and nanoparticle metabolism also need to be considered.

6 Conclusions and outlook

Due to the intensification of the aging of the population, neurodegenerative diseases, especially AD, have become one of the most serious obstacles to social development. This review comprehensively summarized the recent research for modulating amyloid aggregation associated with neurodegenerative diseases, including AD based on nanomaterials and nanotechnology. In this review, nanomaterials exhibited multiple roles in the treatment of AD. Firstly, nanomaterials can directly interact with Aβ peptides and accelerate or slow down amyloid aggregation. Secondly, as nanocarriers, nanomaterials can also be used to load various drugs and assist drugs to across the BBB and inhibit amyloid. In addition, nanomaterials and drugs can synergistically resist a series of problems arising from amyloid aggregation. Moreover, some advanced nanomaterials with photosensitivity can strongly affect amyloid aggregation through PTT or PDT.²⁷⁷ Multiple interaction mechanisms such as electrostatic interaction, hydrophobic interaction, π - π stacking, and metal ion chelation are the main reasons for amyloid fibrillation, and taking advantage of these interactions in the design process and application process, nanomaterials can effectively adsorb amyloids on their surface and block the amyloid aggregation. As novel treatment methods, advanced nanomaterials with the function of PTT and PDT have the advantages of accuracy, ease of administration, high efficiency, and few side effects. In PDT treatment, nanomaterials can generate ROS and oxidize the amino acid residue of amyloid, and then the aggregation process of amyloid is inhibited. In PTT treatment, because the amyloid formation is highly dependent on temperature, the change of localized temperature can affect amyloid aggregation. Currently, PDT and PTT have attracted more and more attention from researchers, and these methods may be the focus of follow-up research. In the future, a deep and comprehensive understanding of the functional

design of nanomaterials and the properties of these nanomaterials is still necessary. The mechanism of action of nanomaterials in AD treatment, especially the in-depth research mechanism of amyloid, including interaction and photo-inhibition process, also needs to be further explored. From the current point of view, the development of nanomaterials has shown a new chapter in the treatment of AD.

Regarding the application of nanomaterials for inhibiting amyloid, there are several aspects to note: (1) in order to successfully achieve clinical applications, it is necessary to further understand and explore the *in vivo* distribution and metabolism of nanomaterials. In future research, it is necessary to continue in-depth research on the biological properties, preparation processes, and surface modification of nanomaterials to achieve a more safe and more efficient inhibition of amyloid aggregation and disaggregation of amyloid fibrils. (2) The BBB permeability of nanomaterials can be improved through some conjugates such as transferrin (*via* transferrin receptor-mediated endocytosis to cross the BBB), and transiently disrupting the blood-brain barrier by physical methods such as photothermal and intranasal administration may also be an effective method. (3) To predict the interactions between amyloid/fibrils and nanoparticles in advance, it is also necessary to build suitable computational models and deeply explore how amyloid/fibrils and nanoparticles interact. (4) Most nanomaterials interact with amyloid through non-covalent interactions, which are weak and may cause reversible aggregation/disaggregation processes, and covalent modulators can prolong their duration of action. PDT and PTT also can directly irreversibly modulate the amyloid fibrosis process. (5) The role of nanomaterials and amyloid at the cellular level and *in vivo* is worth further research in the future, which will provide a strong basis for a biological experiment for nanomaterials to transform nanomedicines. (6) For precise inhibition, the problem of targeting needs to be solved urgently. Targeting ligands have been introduced, such as antibodies, peptides, and aptamers. The amyloid targeting ligand may lose or weaken its binding affinity to amyloid during PDT or PTT, so it is crucial to develop targeting ligands with high stability and strong affinity under harsh conditions. (7) Many studies have pointed to oligomers, and the subsequent application of nanomaterials in oligomers will become the focus and be further explored. (8) Although studies have shown that nanomaterials have a good inhibition efficiency *in vitro*, the inhibition efficiency needs to be further improved *in vivo*. To prove whether the addition of nanomaterials can restore the normal function of nerve cells, various experiments *in vivo* including clinical research still need to be carried out.

Conflicts of interest

The authors declare no conflict of interest.

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