A sustainable hybrid aerogel based on β-lactoglobulin amyloid fibril/UiO-66-NH$_2$ is developed for environmental remediation. The hybrid aerogel’s CO$_2$ capture and water purification performances were investigated. The hybrid aerogel can achieve CO$_2$ capture and possesses excellent adsorption capacities for several heavy metals, dyes, and organic solvents.

Toxic pollutants, such as heavy metals and organic compounds, impart deleterious effects on human health and thus trigger global concerns. In addition, the planetary boundary of climate change has already been exceeded, and is causing irreversible damage to the Earth. Therefore, several water purification and CO$_2$ capture approaches have been introduced. Although these technologies are both reliable and efficient, they are not sustainable due to high energy demands and costs. Therefore, developing sustainable and environmentally-friendly technologies is crucial. Metal–organic frameworks (MOFs) are highly porous nanostructures comprising metal ions/clusters and organic linkers with exceptional characteristics, such as high porosity and surface area, diversity, and flexibility. These properties enable MOFs to possess superior potential in adsorption, gas capture, and separation, as well as environmental remediation. Zirconium-based MOFs, UiO-66, and UiO-66-NH$_4$ have high hydrothermal stability, which is beneficial for water applications. Furthermore, amino groups in UiO-66-NH$_4$ allow for CO$_2$ adsorption properties. However, certain limitations exist for direct application of powdered MOFs, such as poor processability due to fragile and crystalline structures, as well as aggregation issues. We hereby design hybrid MOF-amyloid fibril materials capable to meet the above challenges.

Amyloid fibrils can be prepared by self-assembly of various proteins under proper denaturation and hydrolysis conditions. Different advanced materials based on amyloid fibrils have been developed, such as aerogels, hydrogels, and membranes. Indeed, it has been shown that amyloid fibrils can remove microplastics, heavy metals, dyes, and organic matter from water. In this study, β-lactoglobulin (β-Lg) was used to produce amyloid fibrils, since it is not only the most abundant protein in whey (a by-product of cheese manufacturing), but it is also a globular protein that can easily self-assemble into amyloid fibrils. The hybrid UiO-66-NH$_2$/β-Lg amyloid fibril aerogel is subsequently studied for two critical environmental applications: CO$_2$ capture and water purification.

The hybrid aerogel was prepared by a green and straightforward protocol, schematically described in Fig. 1a, with the details elaborated in the experimental section. The morphology and structure of UiO-66-NH$_2$ were assessed by TEM analysis, showing the octahedral shape of UiO-66-NH$_2$ with a particle size in the range of 80–100 nm. The element mapping images of UiO-66-NH$_2$ in Fig. 1c indicate that the elements Zr, C, N, and O were distributed uniformly in the composite. As shown in Fig. S1a (ESI†), the N$_2$ sorption isotherm of UiO-66-NH$_2$ was type IV, indicating a microporous structure and more than 60% of the pore volume is linked with the pores smaller than 2 nm. The N$_2$ sorption results are presented in Table S1 (ESI†). The N$_2$ sorption isotherm and the surface area, pore radius, and pore volume of the hybrid aerogels are shown in Fig. S1b and Table S1 (ESI†). As shown in Fig. S2 (ESI†), the isoelectric point for UiO-66-NH$_4$ was reached when the pH value was approximately 3.4. UiO-66-NH$_2$ had positive charges at the condition of pH 2 amyloid fibrils solution, which is beneficial for the adsorption of negatively-charged molecules and compounds.

In Fig. 2a, the hybrid aerogel’s homogenous and highly porous structure can be observed by SEM. Fig. 2b and Fig. S3 (ESI†) demonstrate the distribution of the regular-shaped...
UiO-66-NH₂ particles on the amyloid network surface. The hybrid aerogels were ultralight and robust, the density was approximately 40 mg cm⁻³, and the Young’s modulus was approximately $E = 2.0 \times 10^2$ MPa (Table S2, ESI†). The compressive strain and stress curve of the hybrid aerogel is shown in Fig. S4 (ESI†). XRD patterns presented in Fig. 2c reveal the purity and crystallinity of the materials. The pattern of amyloid fibrils had no diffraction peaks and exhibited a broad amorphous peak due to $\beta$-Lg. The pattern of UiO-66-NH₂ was in accordance with previous literature, indicating that pure and crystalline UiO-66-NH₂ was successfully synthesized. The pattern contains the characteristic main peaks of UiO-66 at 2θ = 7.34° and 8.48°. Moreover, the presence of the $\beta$-NH₂ group in UiO-66 did not affect the XRD pattern due to the MOF structure. In the pattern of the hybrid aerogel, the same characteristic peaks of UiO-66-NH₂ can be seen, suggesting that the hybridization with amyloid fibrils did not influence the crystal structure of UiO-66-NH₂. Given the amorphous nature of the MOF/amyloid interface, high-resolution techniques such as gel-state NMR spectroscopy can be considered for future studies to provide additional insights regarding local structures and interactions. The thermal stability of the aerogel was evaluated by thermogravimetric analysis (TGA) and shown in Fig. S5 (ESI†). No significant weight change was observed in N₂ or air up to 250 °C, indicating a good thermal stability of the hybrid aerogel. The interaction between amyloid fibrils and UiO-66-NH₂ was also investigated using FTIR spectroscopy (Fig. 2d). For UiO-66-NH₂, the bands at 3475 and 3363 cm⁻¹ can be assigned to N–H symmetric and asymmetric vibrations, respectively. A wide and medium absorbance feature at approximately 3300 cm⁻¹ proves the existence of H-bonded hydroxyls. The absorption band at 1570 cm⁻¹ indicates the presence of the reaction of –COOH with Zr. The doublet at 1421 and 1387 cm⁻¹ are attributed to the stretching modes of the carboxylic groups in the organic linker. The bands at 1337 and 1258 cm⁻¹ are due to C aromatic–N vibration. The observed peaks between 600–800 cm⁻¹ represent Zr–O as longitudinal and transverse modes. The FTIR spectrum of amyloid fibrils exhibits the amide I region at 1630 cm⁻¹, reflecting C=O stretching vibration and the amide II region at 1525 cm⁻¹, due to N–H bending vibration and C–N stretching vibration, and the amide III region at 1230 cm⁻¹ in the protein. The broad peak at approximately 3270 cm⁻¹ can be ascribed to the –OH vibration. The slight shifts of peaks in the hybrid aerogel pattern can be attributed to the formation of hydrogen bonds between amyloid fibrils and UiO-66-NH₂ at the interface. Furthermore, two new peaks in the region between 900–1200 cm⁻¹ appear which are tentatively attributed to the shift of carboxyl stretch of UiO-66-NH₂, caused by the interaction of amyloid fibrils and UiO-66-NH₂.

Fig. 3 presents the CO₂ capture performance of hybrid aerogels for different loadings of UiO-66-NH₂ near ambient temperature. The CO₂ uptake of the pure UiO-66-NH₂ and the hybrid aerogels containing 30%, 40%, and 50% UiO-66-NH₂ (weight percentage) were 1.14, 0.11, 0.16, and 0.25 mmol g⁻¹, respectively. The performance of pure UiO-66-NH₂ was comparable with published data of approximately 1.6 mmol g⁻¹. Measurements of pure amyloid aerogel revealed that amyloid

UiO-66-NH₂ particles on the amyloid network surface. The hybrid aerogels were ultralight and robust, the density was approximately 40 mg cm⁻³, and the Young’s modulus was approximately $E = 2.0 \times 10^2$ MPa (Table S2, ESI†). The compressive strain and stress curve of the hybrid aerogel is shown in Fig. S4 (ESI†). XRD patterns presented in Fig. 2c reveal the purity and crystallinity of the materials. The pattern of amyloid fibrils had no diffraction peaks and exhibited a broad amorphous peak due to $\beta$-Lg. The pattern of UiO-66-NH₂ was in accordance with previous literature, indicating that pure and crystalline UiO-66-NH₂ was successfully synthesized. The pattern contains the characteristic main peaks of UiO-66 at 2θ = 7.34° and 8.48°. Moreover, the presence of the $\beta$-NH₂ group in UiO-66 did not affect the XRD pattern due to the MOF structure. In the pattern of the hybrid aerogel, the same characteristic peaks of UiO-66-NH₂ can be seen, suggesting that the hybridization with amyloid fibrils did not influence the crystal structure of UiO-66-NH₂. Given the amorphous nature of the MOF/amyloid interface, high-resolution techniques such as gel-state NMR spectroscopy can be considered for future studies to provide additional insights regarding local structures and interactions. The thermal stability of the aerogel was evaluated by thermogravimetric analysis (TGA) and shown in Fig. S5 (ESI†). No significant weight change was observed in N₂ or air up to 250 °C, indicating a good thermal stability of the hybrid aerogel. The interaction between amyloid fibrils and UiO-66-NH₂ was also investigated using FTIR spectroscopy (Fig. 2d). For UiO-66-NH₂, the bands at 3475 and 3363 cm⁻¹ can be assigned to N–H symmetric and asymmetric vibrations, respectively. A wide and medium absorbance feature at approximately 3300 cm⁻¹ proves the existence of H-bonded hydroxyls. The absorption band at 1570 cm⁻¹ indicates the presence of the reaction of –COOH with Zr. The doublet at 1421 and 1387 cm⁻¹ are attributed to the stretching modes of the carboxylic groups in the organic linker. The bands at 1337 and 1258 cm⁻¹ are due to C aromatic–N vibration. The observed peaks between 600–800 cm⁻¹ represent Zr–O as longitudinal and transverse modes. The FTIR spectrum of amyloid fibrils exhibits the amide I region at 1630 cm⁻¹, reflecting C=O stretching vibration and the amide II region at 1525 cm⁻¹, due to N–H bending vibration and C–N stretching vibration, and the amide III region at 1230 cm⁻¹ in the protein. The broad peak at approximately 3270 cm⁻¹ can be ascribed to the –OH vibration. The slight shifts of peaks in the hybrid aerogel pattern can be attributed to the formation of hydrogen bonds between amyloid fibrils and UiO-66-NH₂ at the interface. Furthermore, two new peaks in the region between 900–1200 cm⁻¹ appear which are tentatively attributed to the shift of carboxyl stretch of UiO-66-NH₂, caused by the interaction of amyloid fibrils and UiO-66-NH₂.

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amyloids.36,37 Therefore, the hybrid aerogels possessed a larger capacity for CO2 capture performance.14 The micropores in UiO-66-NH2 favored the transport of CO2 to binding sites and the retention of CO2, which is related to physical adsorption. In addition, the interactions of amino groups in UiO-66-NH2 with CO2 molecules were responsible for CO2 capture performance.14 The results demonstrated that the adsorption capacity of the materials was maintained after three consecutive cycles of CO2 sorption–desorption, confirming the high durability and reversibility of the hybrid aerogels.

Fig. S7 and S8 (ESI†) show the removal performances of the hybrid aerogels for different heavy metals. The mechanism for heavy metal adsorption is mainly attributed to the chemical chelation between amino acids on the amyloid surface and the heavy metal ions.38 The results revealed that the hybrid aerogels had a much higher capacity for Au3+ (547 mg g\(^{-1}\)) and Pt4+ (186 mg g\(^{-1}\)) than the pure amyloid fibrils aerogel. While the hybrid aerogels demonstrated excellent capacity for Cr6+ (308 mg g\(^{-1}\)) and Fe3+ (226 mg g\(^{-1}\)), amyloid fibril aerogel showed no capacity for these metals. Additionally, the hybrid aerogels exhibited high removal efficiency for Au3+, Fe3+, and Pt4+. The improved performance of the hybrid aerogel can be ascribed to UiO-66-NH2. The adsorption mechanism of UiO-66-NH2 is expected to be the ion exchange and electrostatic effect of –NH2 and –COOH groups, combined with the material’s nano-porous structure.39,40 To investigate the competitive adsorption, the hybrid aerogel was immersed in a mixture solution containing 10 heavy metals, the results of which are presented in Fig. S9 (ESI†). The data demonstrate that the aerogel had high adsorption efficiency for Au3+, Fe3+, and Ag+. The efficiency for Pt4+ was much lower compared with the separately conducted adsorption experiment, which might be because Ag+ adsorbed faster than Pt4+, and they share the same binding sites. After the adsorption of Ag+, there were probably fewer binding sites available for Pt4+. Compared with other type of adsorbents (see Table S3, ESI†), the hybrid aerogels in this work exhibited excellent adsorption capacity for Au3+, which could be attributed to the synergies of UiO-66-NH2 and amyloid fibrils. Fig. S10 (ESI†) shows the fitted binding isotherm of Au(0),41 indicating the redox reaction between the hybrid aerogel and Au3+.

The capability of hybrid aerogels for removing organic dyes was also investigated. The results shown in Fig. 4b and c indicate that the removal capacity for Rhodamine B, Crystal violet, Methylene blue, and Malachite green were 54.8, 27.1, 25.2, and 29.6 mg g\(^{-1}\), respectively. The adsorption can be explained mainly by the hydrophobic interactions between the benzene ring of dyes and the hydrophobic domains of the amyloid fibrils. Moreover, Fig. 4d shows the rapid adsorption of n-hexane stained with Oil Red O within 10 s by the hybrid aerogel (ESI† Movie available). The reason for the excellent oil adsorption performance might be that the highly porous structure of the hybrid aerogel provides abundant capillary tunnels that drive the oil to pass through by capillary force rapidly,42 and the oil remained trapped within interconnected micropores.43
To evaluate the reusability of the hybrid aerogels, three subsequent adsorption-regeneration experiments were conducted and the results are presented in Fig. 4e–g. The basis adsorption performances, which means 100%, were obtained from fresh aerogels. The changes in adsorptions performance are illustrated by light color in each panel. For Crystal violet, the performance for cycle 1, 2, and 3 increased by 16.8%, 2.7%, and 3.6%, respectively. The performance improvement could be explained by introducing new hydrophobic binding sites by methanol treatment.2 The washing could also increase the surface area and roughness of the aerogel by removing other impurities.44 For Fe$^{3+}$ and Pt$^{4+}$, the performances decreased after washing, which might be because the regeneration cannot remove all of the pollutants, leading to fewer binding sites available for the next cycle.

Conflicts of interest

There are no conflicts to declare.

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