



# Millisecond self-heating and quenching synthesis of Fe/carbon nanocomposite for superior reductive remediation

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## ABSTRACT

Fe<sup>0</sup>-based nanomaterials are extensively applied in environmental remediation, but their passivated oxide shell restricts deep application. However, efforts aimed at revitalizing Fe-oxide shells have shown limited success. Here, we report a “faster win fast” approach by preferential carbon layer deposition in milliseconds to block Fe-oxide shell growth via carbon-assisted flash Joule heating (C-FJH) reaction. C-FJH induced ultra-high temperature and electric shock promoted reductive Fe formation and subsequently melted to a phase-fusional heterostructure (Fe<sup>0</sup>/FeCl<sub>2</sub>). Therefore, theoretical calculation confirmed that electron delocalization effect of derived heterostructure promoted electron transfer. Synchronously, rapid self-heating/quenching rate (~10<sup>2</sup> K/ms) realized a thin aromatic-carbon layer deposition to sustain both high stability and activity of reductive Fe. The channels of thin aromatic-carbon layer favored inward diffusion of pollutants, which facilitated the subsequent reduction. Accordingly, derived heterostructure and carbon layer jointly contributed to the boosted removal of multiple pollutants (including metal oxyanions, perfluorinated compounds, and disinfection by-products).

## 1. Introduction

Seminal studies on Fe<sup>0</sup>-based nanomaterials have made remarkable strides in environmental remediation because of the strong reducibility and environmental benignity of these materials [1–3]. However, to prevent self-overoxidation, Fe<sup>0</sup>-based materials carry a thick and passive Fe-oxide shell structure, thus deteriorating Fe<sup>0</sup> reactivity by blocking inward mass transport and outward electron transfer [4,5]. To overcome the low reactivity of Fe<sup>0</sup>, numerous investigators endeavored to revitalize the oxide shell of Fe<sup>0</sup>. For instance, carbon-based material can be employed as a carrier to improve the dispersion and surface area of Fe<sup>0</sup>-based materials, thereby improving the enrichment/adsorption

performance of pollutants [6,7]. Furthermore, nano-cracks can be opened on the dense Fe-oxide shell structure through the embrittlement effect of liquid nitrogen or Kirkendall effect of phosphorylation [5,8]. Although these methods based on oxide shell revolution can enhance Fe<sup>0</sup> activity to some degree, the rapid re-formation of the Fe-oxide shell compromises again the Fe<sup>0</sup> reactivity [7,8]. Therefore, improving the long-term reactivity of Fe<sup>0</sup>-based nanomaterials still are a bottleneck [9].

In essence, a dense Fe-oxide shell structure is derived from rapid self-oxidation of Fe<sup>0</sup> within minutes [10]. Therefore, we proposed a new “faster win fast” strategy to inhibit Fe-oxide shell growth. In this method, a “thin skin” faster deposited on the surface of Fe<sup>0</sup> within

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milliseconds. Synchronously, this new skin should guarantee to not inhibit  $\text{Fe}^0$  activity. Highly aromatic carbon typically has a large number of adsorption sites that favor the diffusion of pollutants [11,12], thus we imagine carbon layer can cooperate with  $\text{Fe}^0$  to synergistically boost the reduction performance [7,13]. Opportunely, an emerging carbon-assisted flash Joule heating (C-FJH) technology can accomplish the aforementioned hypothesis [14,15]. Firstly, the C-FJH reaction induced ultra-high temperature ( $> 3000\text{ K}$ ) and electric shock can promote the crack chemical bond of Fe-containing precursor to form reductive Fe components such as  $\text{Fe}^0$  and  $\text{Fe}^{2+}$  [14]. At this temperature and during the C-FJH process, the rapid self-heating/quenching rate ( $\sim 4000\text{ K}$ ,  $\sim 10^2\text{ K/ms}$ ) could ensure the volatiles derived from carbon substrate decomposition instantly deposit on the surface of Fe component within milliseconds [14]. Therein, the rapid self-heating/quenching process can be realized by programmed control reaction time (millisecond level) and input current. In addition, C-FJH induced thin aromatic-carbon layer should have a similar function to graphene in protecting reductive Fe components from oxidation [16, 17].

Additionally, C-FJH may confer multiple benefits. For example, the C-FJH reaction induced ultra-high temperature can pass the boiling point of metallic elements, resulting in metallic components present in liquid and interfusion forms. Thus, reductive bi-components ( $\text{Fe}^0$  and  $\text{Fe}^{2+}$ ) can fuse to form a phase-fusional heterostructure. Accordingly, the compositional flexibility of phase-fusional heterostructures could reinforce the ability of atomic orbital hybridization to improve the reductive capacity via electron delocalization effect [18,19]. Moreover, rapid quenching rates can hinder metal aggregation, ultimately resulting in highly-reactive metals with minor sizes that further enhance the material reactivity [20,21]. Undoubtedly, the C-FJH reaction can realize a “three birds with one stone” material characterized by oxide shell-free, partial phase-fusional heterostructure, and nano-size, thus opening a new era for reductive Fe-based nanomaterials.

In this work, we report a customized C-FJH process to synthesize oxide shell-free of Fe/carbon nanocomposite. We compared the functions and performance of  $\text{Fe}^0$ -based materials produced using conventional  $\text{NaBH}_4\text{-R}$  ( $\text{NaBH}_4$  reduction) and  $\text{H}_2\text{-R}$  ( $\text{H}_2$  reduction) methods. As a proof-of-concept, multiple pollutants including perfluorooctane sulfonate (PFOS), perfluorooctanoic acid (PFOA),  $\text{Cr(VI)}$ ,  $\text{Sb(V)}$ , and dichloroacetic acid (DCAA) were tested. We also expanded C-FJH technology to synthesize oxide shell-free of Cu or Ag/carbon nanocomposite as virus-inactivating agents for pepper mild mottle virus (PMMoV).

## 2. Experimental

### 2.1. Synthesis of reductive Fe /carbon nanocomposite by C-FJH reaction

A homemade C-FJH device was utilized to synthesize a robust Fe/carbon nanocomposite. Briefly, hydrochar and metallic salt with the same mass were uniformly mixed in anhydrous ethanol by oscillation and then suspended in a  $60\text{ }^\circ\text{C}$  vacuum oven to dry. Next, 10 wt% carbon black (conductive additive) was mixed with the dried solid mentioned above for C-FJH treatment. Finally, 0.1 g of the mixture was put into a quartz tube (tube thickness: 2 mm, inner diameter: 6 mm, length: 45 mm) and compressed with copper electrodes to minimize the sample resistance to  $\sim 100\ \Omega$ . Then, a gentle vacuum was maintained during the reaction and purged with nitrogen to avoid sample oxidation. Finally, Fe/carbon nanocomposites were synthesized by adjusting C-FJH pulse voltage. A 50 ms duration time and 150–250 V pulse voltage were chosen as the flash Joule heating condition in this work. The preparation procedure for Cu or Ag/carbon nanocomposite is the same as above. More details can be found in the [Supporting information](#).

### 2.2. Characterization of reductive Fe/carbon nanocomposite

The heterostructure-Fe was demonstrated by high-resolution electron microscopy (HR-TEM). HR-TEM equipped with energy dispersive X-ray spectrometry (EDX) and high-angle annular dark-field (HAADF) images were performed to analyze elemental distributions and surface morphology. The distribution of Fe/carbon composite size was obtained using Nano Measurer 1.2 software to analyze TEM images of at least 100 particles. The composition and structure information of the as-prepared sample was analyzed by electron energy-loss spectroscopy (EELS) and X-ray absorption fine structure (XAFS). The free corrosion potentials and the charge transfer resistance was determined by Tafel and Electrochemical impedance spectroscopy (EIS) measurement, respectively. More details can be found in the [Supporting information](#).

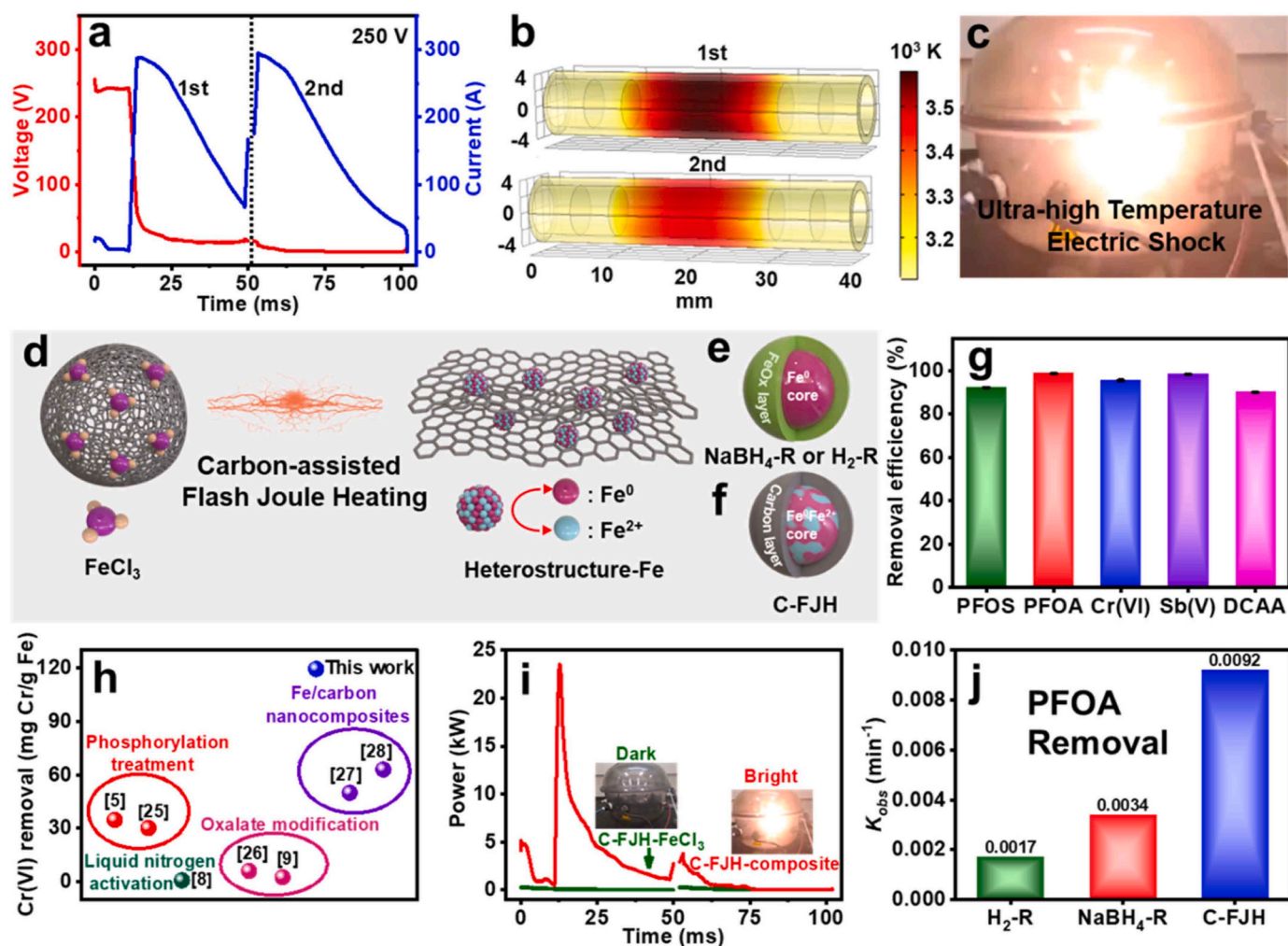
## 3. Results and discussion

### 3.1. C-FJH advantages on reductive Fe/carbon nanocomposite fabrication

The C-FJH technology was compared with conventional chemical reduction ( $\text{NaBH}_4\text{-R}$  and  $\text{H}_2\text{-R}$ ) on fabricating reductive Fe/carbon nanocomposites. To initiate the C-FJH reaction, the mixture of  $\text{FeCl}_3$  (precursor of reductive component), hydrochar (heating element), and carbon black (conductor) was compacted by two copper electrodes and then powered by a pulse voltage (Fig. 1a, Fig. S1). Accordingly, variable transient current-induced Joule heating resulted in an instantaneous temperature increase to  $\sim 4000\text{ K}$  (Fig. 1b, Fig. S2), as clearly seen by the dazzling light (Fig. 1c). Tuning the applied electrical pulse may affect the performance of the as-prepared reductive materials. The ultra-high temperature, electric shock, and rapid quenching rate are important features of the C-FJH reaction and may endow the as-prepared material with a carbon-encased phase-separated heterostructure or alloy structure (Fig. 1d) [14,22,23]. Regarding the fact that the Fe-oxide shell of  $\text{Fe}^0$  can significantly hinder mass transport and electron transfer, thus decreasing the reactivity of  $\text{Fe}^0$  (Fig. 1e) [24]. Accordingly, we predicted that the C-FJH-derived sample features a unique structure with an unprecedented reductive capacity (Fig. 1f), as confirmed by its high efficiencies ( $> 90\%$ ) for removing multiple pollutants including PFOS, PFOA,  $\text{Sb(V)}$ ,  $\text{Cr(VI)}$ , and DCAA (Fig. 1g). This view is further verified by comparing with other reported reductive capacities of  $\text{Fe}^0$ -based materials (Fig. 1h) [5,8,9,25–28].

The role of carbon substrate (hydrochar) in fabricating reductive Fe/carbon nanocomposite by C-FJH reaction was further investigated. As shown in Fig. 1i, the C-FJH reaction was not initiated even when a high voltage was applied to  $\text{FeCl}_3$  alone, as confirmed by the power and darkness of the as-prepared sample. Contrarily, the C-FJH reaction proceeded with the assistance of a carbon substrate because sufficient Joule heat was provided from the hydrochar via the Joule heating effect. Thus, carbon substrate for the C-FJH reaction is indispensable when fabricating reductive materials, as confirmed by the  $\text{Cr(VI)}$  removal results (Figs. S3–4).

Herein, taking “forever chemicals” PFOA and easily reduced  $\text{Cr(VI)}$  as probe indicators [29], we evaluated the reductive capacity of the as-prepared material. Compared to  $\text{H}_2\text{-R}$  and  $\text{NaBH}_4\text{-R}$  methods, C-FJH treatment significantly improved PFOA or  $\text{Cr(VI)}$  removal rate by more than 2.7 or 2.8-fold, respectively (Fig. 1j, Fig. S5–6). Clearly, the pollutants removal capacity of the C-FJH-derived sample was much higher than that of  $\text{H}_2\text{-R}$ - and  $\text{NaBH}_4\text{-R}$ -derived samples (Fig. S7), implying the highly reactive Fe of the C-FJH-derived sample (Fig. S8). In addition, the adsorption effect of the carbon substrate on pollutants removal was minor, indicating that the carbon substrate only provides adsorption sites in pollutants removal (Fig. S9). A previous study showed that surface area of material can influence the pollutants removal performance [30], so we calculated the surface-area-normalized PFOA and  $\text{Cr(VI)}$  removal rate constant  $k'$ . Compared to the  $\text{H}_2\text{-R}$ - and



**Fig. 1.** Synthesis of reductive Fe/carbon nanocomposites and their performance in Cr(VI) removal. (a) Recorded current and voltage in carbon-assisted flash Joule heating (C-FJH) process. (b) 3D mapping temperature field simulation under C-FJH via COMSOL Multiphysics software. (c) Real-time photos of sample during the C-FJH process. (d) Schematic diagram for mechanism of reductive Fe/carbon nanocomposite preparation. (e) Core-shell structure of Fe<sup>0</sup> obtained using traditional preparation procedures. (f) Reductive Fe/carbon nanocomposite prepared using the C-FJH reaction. (g) Removal efficiencies of PFOS, PFOA, Cr(VI), Sb(V), and DCAA with Fe/carbon composite prepared by C-FJH. (h) The Cr(VI) removal capacity of reductive Fe was compared with reported reduction materials. (i) Power generated in C-FJH reaction with only FeCl<sub>3</sub> or a mixture of hydrochar and FeCl<sub>3</sub> precursor. (j) Comparison of apparent PFOA removal rate constant  $k_{obs}$  of different Fe/carbon composites prepared by C-FJH and conventional NaBH<sub>4</sub>-R or H<sub>2</sub>-R methods. (Experimental parameters: [PFOS] or [PFOA] = 0.1 mg L<sup>-1</sup>, reaction time = 1 h, reaction time = 2 h, dose of sample, 1 g L<sup>-1</sup>; [Cr(VI)] = 10 mg L<sup>-1</sup>, reaction time = 1 h, dose of sample, 1 g L<sup>-1</sup>; [Sb(V)] = 5.11 mg L<sup>-1</sup>, reaction time = 24 h, dose of sample = 2.5 g L<sup>-1</sup>; [DCAA] = 10.66 mg L<sup>-1</sup>, reaction time = 72 h, dose of sample = 3 g L<sup>-1</sup>, initial pH = 4.0; temperature, 25 °C.).

NaBH<sub>4</sub>-R-derived samples, the C-FJH-derived sample had a higher  $k'$  value but a relatively small surface area. This result strongly excluded the contribution of surface area enhancement to pollutant removal (Fig. S10).

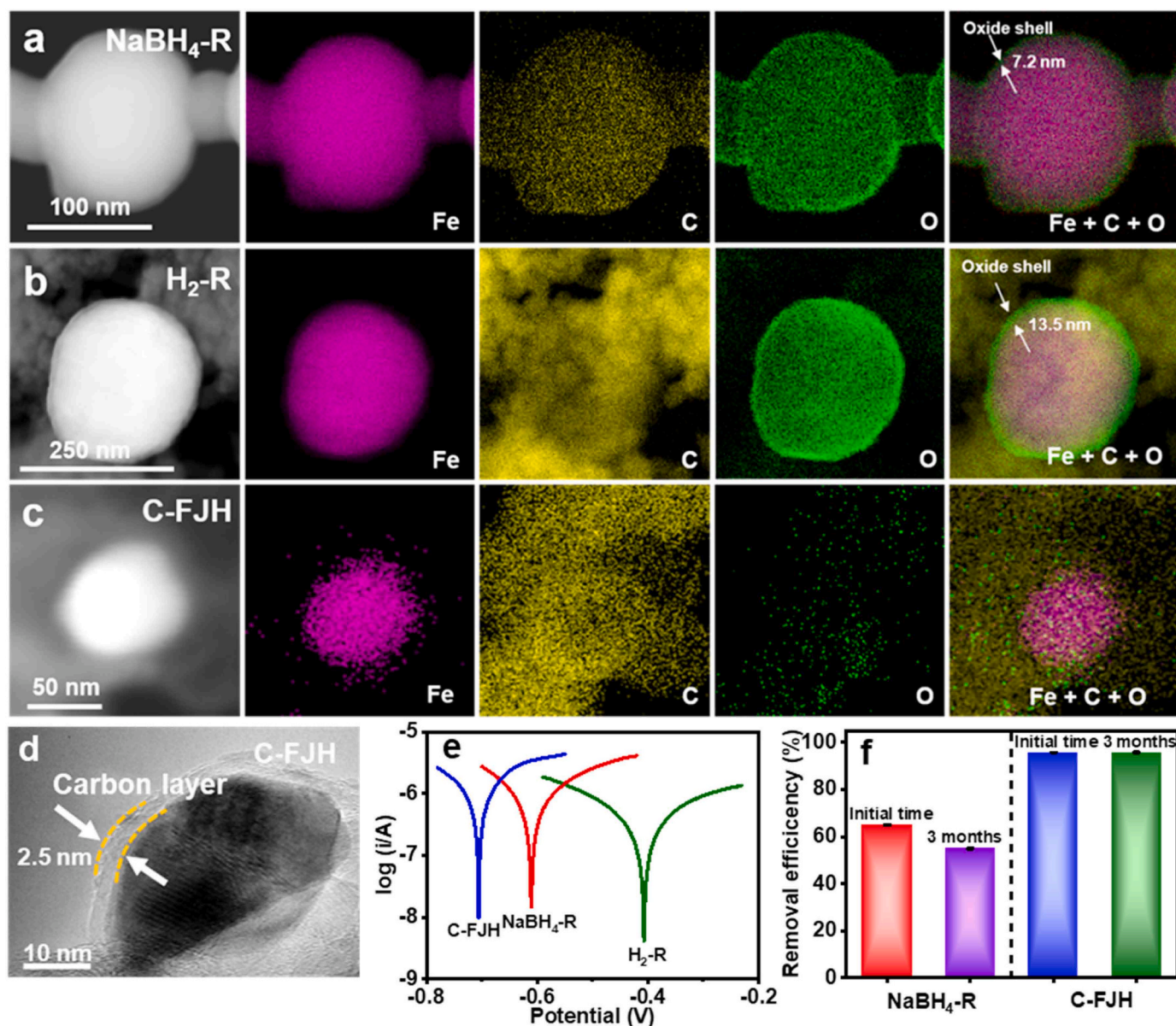
### 3.2. C-FJH induced oxide shell-free and phase-fusional heterostructure

To understand the improved reactivity of the C-FJH-derived sample, we performed various structural analyses of different Fe/carbon composites. Traditional NaBH<sub>4</sub>-R and H<sub>2</sub>-R methods for producing Fe<sup>0</sup> were composed of necklace-like or spherical aggregate with a distinct core-shell structure [5,31], as confirmed by the bright inner core and dim outer shell of HAADF images (Fig. 2a, b). Moreover, Fe + C + O overlapped elemental mapping of EDX results suggested that the Fe core was encapsulated by a dense Fe-oxide shell that was 7.2 and 13.5 nm thick in the NaBH<sub>4</sub>-R- and H<sub>2</sub>-R-derived samples, respectively. Theoretically, the increased Fe-oxide shell can hinder electron transfer from the Fe core to Fe-oxide shell [32], thereby inhibiting the reductive efficiency. Accordingly, the H<sub>2</sub>-R-derived sample with a thicker oxide shell

exhibited an inferior reductive capacity (Fig. S7). Notably, despite numerous efforts attempted to reform the oxide shell of Fe<sup>0</sup> (refs. [5,8,33]), success has been very limited.

Intriguingly, the Fe sphere of C-FJH-derived sample showed no significant color difference, as clearly confirmed by HAADF images (Fig. 2c), strongly implying a lack of the Fe-oxide shell. Subsequently, the scattered distribution of O elements and the absence of dense surface rings confirmed this result, as demonstrated in O and overlapped Fe + C + O elemental mapping. Undoubtedly, the lack of oxide shells decreases the stability of Fe<sup>0</sup>-based materials [34,35]. Therefore, intrinsically maintaining the stability and activity of materials is challenging. Importantly, HR-TEM images strongly confirmed that the inner Fe core of the C-FJH-derived sample was tightly encapsulated by a ~2.5 nm carbon layer (Fig. 2d). Owing to the rapid self-heating/quenching rate during the C-FJH process, the decomposition products of the carbon substrate were instantly deposited on the surface of the Fe component. Additionally, the carbon layer formation rate was overwhelmingly faster than that of oxide shell, thus intensively hindering the oxide shell formation. In general, the coating of the stabilizer on the surface of Fe<sup>0</sup> will





**Fig. 2.** Morphology and surface chemical property analysis. (a) High-angle annular dark-field (HAADF) images of NaBH<sub>4</sub>-R-derived sample and corresponding energy-dispersive X-ray (EDX) elemental mapping of Fe, C, O, and their overlapped images. (b) HAADF images of H<sub>2</sub>-R-derived sample and corresponding EDX elemental mapping of Fe, C, O, and their overlapped images. (c) HAADF images of C-FJH-derived sample and corresponding EDX elemental mapping of Fe, C, O, and their overlapped images. (d) High-resolution transmission electron microscopy (HR-TEM) images of C-FJH-derived sample. (e) Tafel curves of Fe/carbon composite by C-FJH and conventional NaBH<sub>4</sub>-R or H<sub>2</sub>-R methods. (f) Stability analysis of NaBH<sub>4</sub>-R- and C-FJH-derived samples during Cr(VI) removal. (Samples exposed to air for 3 months) Note: To ensure the consistency of the samples, the same proportion of carbon black was added to the raw materials of the three as-prepared samples.

reduce the diffusion channel and block the active site, thus inhibiting the electron transfer of the Fe core to the pollutant [11]. Strikingly, the C-FJH-derived sample presented extraordinarily faster electron transfer, as this sample showed the most negative free corrosion potential (−0.706 V) (Fig. 2e, Fig. S11) [36,37]. In essence, the aromatic-carbon layer can certainly act as a citadel to protect Fe core from oxidation [36, 37]. The C-FJH-derived sample exhibited outstanding stability, as confirmed by high Cr(VI) removal reactivity even exposed to air for three months (Fig. 2f, Fig. S12).

Compared to the dense Fe core of NaBH<sub>4</sub>-R- and H<sub>2</sub>-R-derived samples, the Fe core was relatively sparse and formed numerous nanocracks in Fe elemental mapping of the C-FJH-derived sample (Fig. 2c). Electric shock induced by the C-FJH reaction breaks the magnetic and electrostatic forces within the particles, resulting in the formation of nanocracks. Undoubtedly, nano-cracks can facilitate interfacial electron/

mass diffusion [5].

Moreover, the C-FJH-derived sample showed the smallest average particle size because rapid heating/quenching inhibited metal agglomeration (Fig. S13), which can further increase the exposure of active sites in the sample [38,39]. Thus, the C-FJH reaction can loosen the Fe core and produce a nano-size effect. Obviously, the comprehensive effects in the C-FJH process changed both the bulk structure and surface construction of the Fe core.

From the X-ray diffraction (XRD) patterns in Fig. S14, α-Fe<sup>0</sup> was the only Fe species in the NaBH<sub>4</sub>-R- and H<sub>2</sub>-R-derived samples, whereas γ-Fe<sup>0</sup> and FeCl<sub>2</sub> were the main Fe species in the C-FJH-derived sample. Obviously, the C-FJH reaction can induce specific structural changes in reductive materials, therefore, we applied electron energy-loss spectroscopy (EELS) and X-ray absorption fine structure (XAFS) to obtain the composition and structure information of the C-FJH-derived sample.



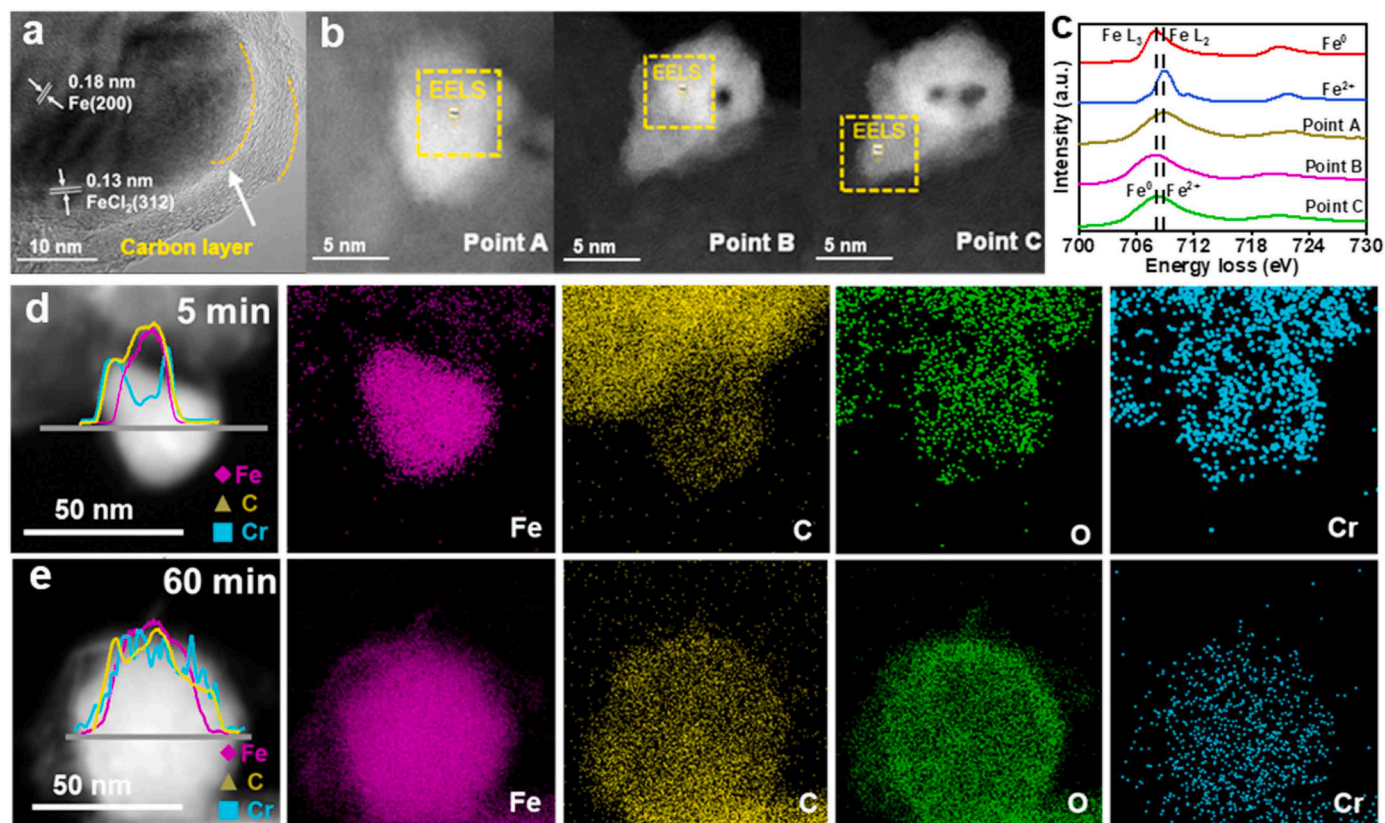
Firstly, HR-TEM images revealed the inner phase is  $\gamma\text{-Fe}^0$  and  $\text{FeCl}_2$  based on lattice spaces of 0.18 and 0.13 nm, respectively, indicating the formation of heterostructure-Fe (Fig. 3a) [40,41]. Furthermore,  $\text{Fe}^0$  and  $\text{Fe}^{2+}$  were evenly distributed over the entire single particle, as confirmed by annular bright-field scanning (ABF) images and the corresponding EELS spectrum (Fig. 3b,c). These results further imply phase-fusional heterostructures formation, as ultra-high temperatures can crack the Fe-Cl bond and subsequently alloy the reductive components during the C-FJH process [14].

As reported previously, the dense Fe-oxide shell can hamper mass transport and electron transfer simultaneously [42]. Therefore, it is urgent to understand why substituting a carbon layer for an oxide shell still maintains the activity of the Fe/carbon nanocomposite. Given the removal process of organics is difficult to observe with an electron microscope. Herein, with Cr(VI) removal as a model reaction, the time-sequence structural evolution of individual Fe spheres was tracked through electron microscopy. After a 5-min reaction, Cr(VI) penetrated the carbon layer and scattered distribution in the inner Fe core of the C-FJH-derived sample, as indicated by the increase in Fe, C, and Cr elemental mapping (Fig. 3d). As the reaction progresses, Cr(VI) is completely distributed on the Fe core, as evidenced by Cr elemental mapping of the C-FJH-derived sample (Fig. 3d,e) [43]. Moreover, in the air atmosphere, the C-FJH-derived sample maintained high-activity because of the oxygen resistance of the carbon layer (Fig. S15).

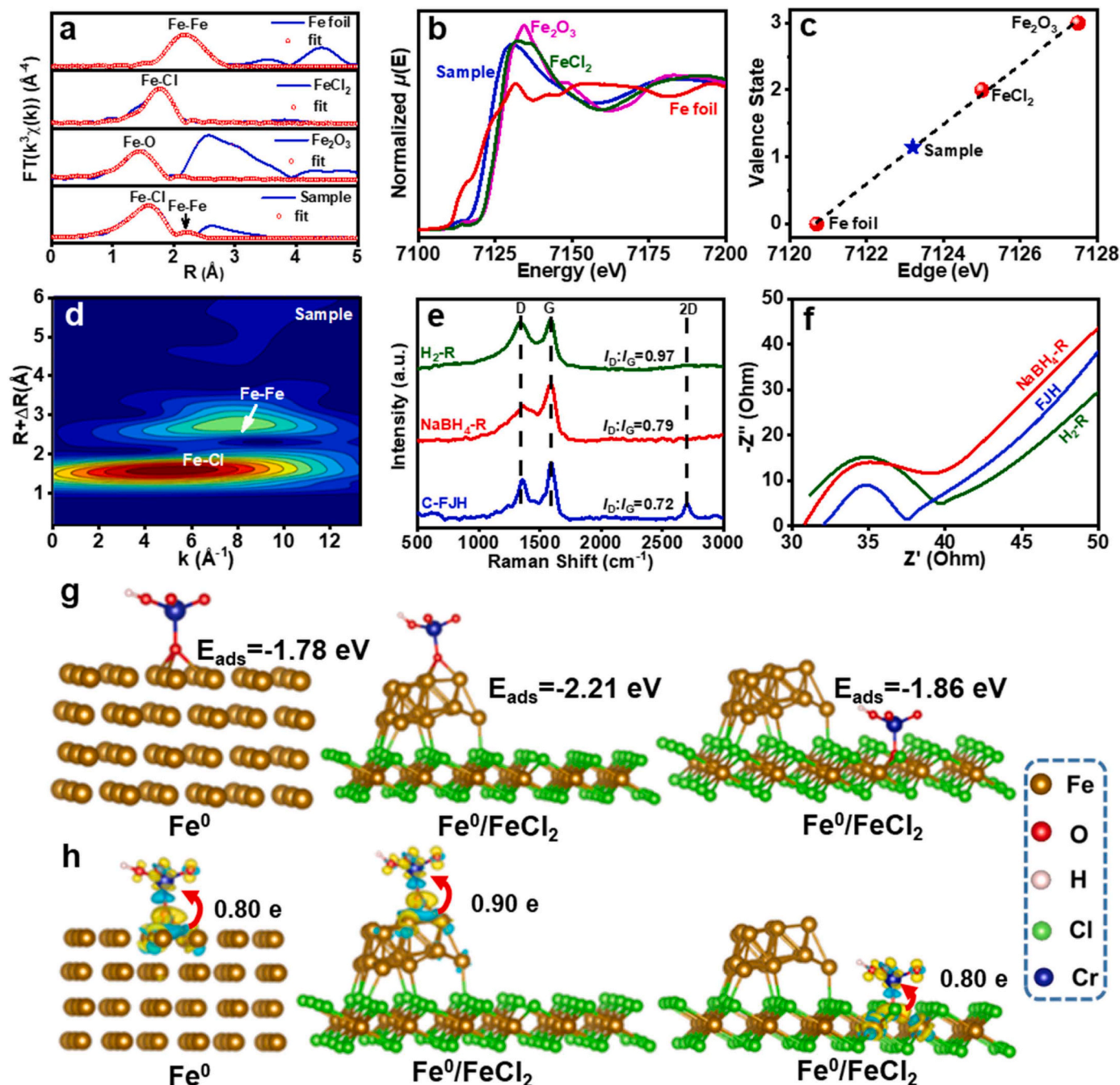
To further probe the oxidation states and coordination environment for C-FJH-derived material, X-ray absorption near-edge structure (XANES) and extended X-ray absorption fine structure (EXAFS) of Fe K-edges were conducted. Fig. 4a presents the  $k^3$ -weighted Fourier transform (FT)-EXAFS spectra of the existence of a Fe-Fe bond at a peak of

2.50 Å, and the radical distance of Fe-Cl decreased to 2.17 Å after C-FJH treatment (Table S1). The Cl coordination number of Fe in the C-FJH-derived sample was reduced from 6 to 5.6, compared to  $\text{FeCl}_2$  standard. Thus, partial cracking of the Fe-Cl bond and Cl volatilization occurred at ultra-high temperatures during the C-FJH process to produce  $\text{Fe}^0$  that filled the Cl position. This result further confirms the occurrence of partial phase fusion, which agrees with the EELS results. Moreover, XANES spectra revealed that the rising edge of the C-FJH-derived sample was situated between Fe foil and  $\text{FeCl}_2$ , suggesting that the Fe atoms were in an intermediate state between  $\text{Fe}^0$  and  $\text{Fe}^{2+}$  (Fig. 4b). The oxidation state of Fe was +1.2 from the Fe K-edge XANES via linear fitting between the valence states of Fe and first inflection point of the derivative spectrum [44], supporting the coexistence of  $\text{Fe}^0$  and  $\text{FeCl}_2$  (Fig. 4c). X-ray photoelectron spectroscopy (XPS) analysis further confirmed the existence of  $\text{Fe}^0$  in the C-FJH-derived sample resulting from breakage of the Fe-Cl bond during the C-FJH process (Fig. S16). The Wavelet transform (WT) also confirmed the existence of Fe-Cl and Fe-Fe coordination, compared to that of the standards (Fig. 4d). Accordingly, a fusion phase was formed after C-FJH treatment, and this unique  $\text{Fe}^0/\text{FeCl}_2$  heterostructure may be the main reason for the enhanced reductive capacity.

Given the critical role of carbon structure in pollutant removal, it is essential to understand how the carbon substrate varies during the C-FJH process. As revealed by the C 1 s XPS spectrum, the abundance ratio of C=C to C-C was the largest in the C-FJH-derived sample, indicating a higher degree of aromatization (Fig. S17, Table S2) [45,46]. Subsequent Raman spectroscopy also confirmed this result (Fig. 4e, Table S2) [15]. The highly aromatic-carbon can promote the diffusion of pollutants via defective channel [11]. Furthermore, the electrochemical impedance



**Fig. 3.** Component analysis and structure evolution during Cr(VI) removal process. (a) HR-TEM images of the C-FJH-derived sample. (b) Annular bright-field scanning (ABF) images of the C-FJH-derived sample. (c) Fe  $L_3$  edge positions of  $\text{Fe}^0$  (708 eV) and  $\text{Fe}^{2+}$  (708.85 eV) for Fe species in the electron energy-loss spectroscopy (EELS) spectrum of the C-FJH-derived sample. (d) HAADF-STEM images of C-FJH-derived sample reacted with Cr(VI) for 5 min and the corresponding EDX elemental mapping of Fe, C, O, Cr. (e) HAADF-STEM images of C-FJH-derived sample reacted with Cr(VI) for 60 min and the corresponding EDX elemental mapping of Fe, C, O, Cr. Note: The removal process of organics is difficult to observe with electron microscopy, so Cr(VI) removal is selected as the model reaction.



**Fig. 4.** Component analysis and reaction mechanism. (a) Extended X-ray absorption fine structure (EXAFS) fitting curves of Fe foil, FeCl<sub>2</sub>, Fe<sub>2</sub>O<sub>3</sub>, and C-FJH-derived sample in R space. (b) Fe K-edge XANES spectra of C-FJH-derived sample. (c) XANES fitting valence of C-FJH-derived sample. (d) Wavelet transform (WT) analysis of C-FJH-derived sample. (e) Raman spectrum of the Fe/carbon composite prepared using C-FJH and conventional NaBH<sub>4</sub>-R or H<sub>2</sub>-R methods. (f) Electrochemical impedance spectroscopy (EIS) curves of the Fe/carbon nanocomposite prepared using C-FJH and conventional NaBH<sub>4</sub>-R or H<sub>2</sub>-R methods. (g) Density functional theory (DFT) calculation of HCrO<sub>4</sub> coordinated with Fe<sup>0</sup> and Fe<sup>0</sup>/FeCl<sub>2</sub>. (h) DFT calculation of charge-density difference in HCrO<sub>4</sub> adsorbed on Fe<sup>0</sup> and Fe<sup>0</sup>/FeCl<sub>2</sub>. The yellow and blue isosurfaces represent the charge accumulation and depletion region, respectively. Note: Models of Fe<sup>0</sup> and the heterostructure Fe<sup>0</sup>/FeCl<sub>2</sub> were constructed to compare the contribution of active species, so no additional carbon layers were added to the models.

spectroscopy results confirmed the C-FJH-derived sample possessed the lowest charge transfer resistance, this contributes to electron transfer (Fig. 4f).

We further studied the effects of C-FJH power on the different Fe/carbon nanocomposites of reductive capacity. The C-FJH reaction becomes more violent as the applied pulse voltage increases, causing the reaction temperature to rise (Fig. 1a, Fig. S2, Fig. S18-19). It was found the pollutant removal efficiency increased from 73.1% to 95.6% with increasing the input power (Fig. S20-21), as evidenced by the faster

electron transport of the higher-power obtained sample (Fig. S22). Because the decomposition temperature of any metal salt is less than 3000 K [14], the strong C-FJH reaction induced by high power can promote cracking of the Fe-Cl bond to produce more reductive Fe. Furthermore, for different iron salt precursors, the Fe/carbon nanocomposite prepared using C-FJH technology exhibited excellent reduction performance (Fig. S23). The bond energy of Fe-Cl (351 KJ/mol) is lower than that of Fe-O ( $390.4 \pm 17.2$  KJ/mol) [47], which can affect the reductive Fe component generated by the C-FJH process, and



ultimately affect the removal effect of pollutants. The subsequent Tafel results can support this inference (Fig. S24). Even at the same input voltage, different Fe precursors (ferric acetate and ferrous oxalate) samples derived from C-FJH can trigger varied Joule heating effects. Raising the current through the sample will cause a sharp rise in the temperature and power of the sample, which will undoubtedly promote the break of chemical bonds to form reductive components. However, excessive temperature will also accelerate the volatilization of metal elements (Fig. S25–27) [14,48]. Tuning the appropriate electrical parameters is the key to obtaining reductive components.

### 3.3. Reduction mechanism of Fe/carbon nanocomposite

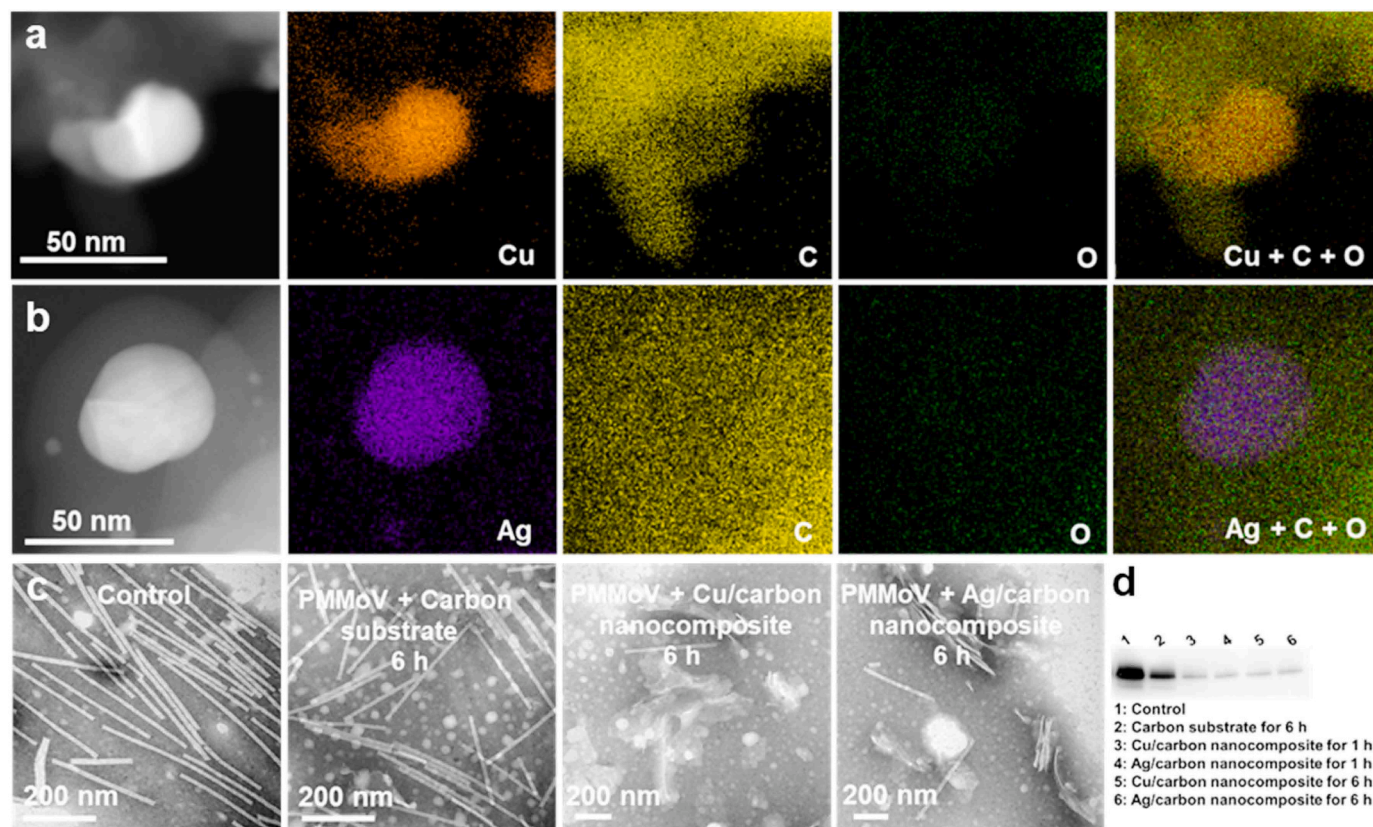
Exemplified by Cr(VI) or PFOA removal, we explored the reduction mechanism of different Fe/carbon composites. Considering Fe(II) plays an indispensable role in pollutant removal [26], therefore, the contribution of Fe(II) to Cr(VI) or PFOA reduction was firstly investigated. The amount of Fe(II) released suggests that Fe(II) may participate in Cr(VI) reduction (Fig. S28a, b). As expected, Cr(VI) removal over H<sub>2</sub>-R- and NaBH<sub>4</sub>-R-derived samples were suppressed to a certain extent by addition of 1,10-phenanthroline, whereas Cr(VI) removal over the C-FJH-derived sample showed almost no change (Fig. S29). This contrast indicates that dissolved Fe(II) played a minor role in removing Cr(VI) from the C-FJH-derived sample. It should be noted that structural Fe(II) ( $E_0 = -0.34$  to  $-0.65$  V) is more reducible than aqueous Fe(II) ( $E_0 = 0.77$  V) [23,49], thus favoring the Cr(VI) reduction. Assuming that all Fe<sup>0</sup> content (1.32  $\mu$ mol) in the C-FJH-derived sample is involved in Cr(VI) reduction (Fig. S30), it can only reduce 15.2% of total Cr(VI). Thus, this result strongly supported the major active component is Fe<sup>0</sup>/FeCl<sub>2</sub> heterostructure for Cr(VI) removal. Considering that Cr(VI) is easy to

reduce, we also tested the effect of Fe(II) on the PFOA removal. Surprisingly, the removal effect of PFOA was slightly suppressed by adding of 1,10-phenanthroline (Fig. S31). Therefore, Fe<sup>0</sup>/FeCl<sub>2</sub> heterostructure can be the main reason for the reduction performance improvement.

Furthermore, we theoretically unraveled the role of heterostructure-Fe in enhancing the reduction performance. Fe<sup>0</sup> is used as the benchmark model, whereas some Fe atoms are placed on the FeCl<sub>2</sub> model to form a Fe<sup>0</sup>/FeCl<sub>2</sub> heterostructure model. The theoretical calculation results presented that the calculated adsorption energy of Cr(VI) on the Fe<sup>0</sup> site or Fe<sup>2+</sup> site of Fe<sup>0</sup>/FeCl<sub>2</sub> heterostructure was  $-2.21$  or  $-1.86$  eV, respectively, obviously lower than that ( $-1.78$  eV) of a single Fe<sup>0</sup> system (Fig. 4g, Fig. S32). These results support that Cr(VI) preferentially coordinates with the Fe<sup>0</sup> sites of the Fe<sup>0</sup>/FeCl<sub>2</sub> heterostructure with lower adsorption energy, which can contribute to the enhanced Cr(VI) removal. Charge-density difference calculations revealed that Cr(VI) adsorbed on a single Fe<sup>0</sup> system accepts electrons from Fe<sup>0</sup> via a single-channel pathway. In contrast, Cr(VI) adsorbed on the Fe<sup>0</sup>/FeCl<sub>2</sub> heterostructure captured electrons in diverse manners, as two types of Fe atoms can combine with Cr(VI). The difference in the electron transfer pathway resulted in a better electron-withdrawing ability of Cr(VI) on the Fe<sup>0</sup>/FeCl<sub>2</sub> heterostructure surface, as reflected by its higher electron transport quantity (Fig. 4h). This is because the electron delocalization effect enabled more electrons to be transferred to the interface of Fe<sup>0</sup> and FeCl<sub>2</sub>, thus favoring the subsequent Cr(VI) reduction [9]. These results confirmed that the Fe<sup>0</sup>/FeCl<sub>2</sub> heterostructure significantly improved reduction properties.

### 3.4. Expansion of C-FJH technology on Cu or Ag/carbon nanocomposite

Until now, obtaining non-oxidized Cu or Ag nanomaterials remains



**Fig. 5.** Expanded application of C-FJH technology. (a) HAADF images of Cu/carbon nanocomposite and corresponding EDX elemental mapping of Cu, C, O, and their overlapped images. (b) HAADF images of Ag/carbon nanocomposite and corresponding EDX elemental mapping of Ag, C, O, and their overlapped images. (c) TEM images of pepper mild mottle virus (PMMoV) treated under different conditions as specified in the images. (d) Western blot analysis of PMMoV incubated with carbon substrate, Cu, or Ag/carbon nanocomposites for 1 or 6 h. (dose of sample =  $3.5 \text{ g L}^{-1}$ ).



challenging [34,35]. To expand the utilization potential of C-FJH technology, we tested this process on preparing Cu or Ag/carbon nanocomposites. Both Cu and Ag/carbon nanocomposites prepared using C-FJH technology lack an obvious oxide shell, as evidenced by O elemental mapping and HAADF images (Fig. 5a,b). In benchmark experiments, both metal-based nanocomposites led to PMMoV fracture and even deformation *in vitro*, whereas PMMoV particles in the untreated group exhibited a baculiform shape and were evenly distributed (Fig. 5c). Besides TEM evidence, western blotting showed that the band corresponding to capsid protein faded away after Cu or Ag/carbon nanocomposites treatment, indicating the rapid loss of viral activity (Fig. 5d, Fig. S33, Table S3) [50,51]. Although the oxide shell is missing, the Cu or Ag/carbon nanocomposites can still maintain high-activity to directly injure PMMoV shell proteins. Therefore, Cu or Ag/carbon nanocomposites prepared by C-FJH technology show potential as virus-inactivating agents for PMMoV.

#### 4. Conclusions

We report an innovative C-FJH process for fabricating a reductive Fe/carbon nanocomposite with excellent removal capacity and longevity. With such an approach, we synthesized materials with multiple benefits, featuring oxide shell-free, partial phase-fusional heterostructure, and nano-size. A highly aromatic-carbon layer derived from C-FJH favors inward diffusion of pollutants, which facilitated to the subsequent reduction. Theoretical calculations indicated that the C-FJH reaction induced phase-fusional  $\text{Fe}^0/\text{FeCl}_2$  heterostructure captures more electrons for decontamination due to the electron delocalization effect. Moreover, the C-FJH-derived sample demonstrated versatility in removing multiple pollutants such as PFOS, PFOA, Sb(V), and DCAA. Importantly, C-FJH also successfully expanded on preparing Cu or Ag/carbon nanocomposites with oxide shell-free structures for high-efficiency virus inactivation. Therefore, C-FJH opens a vast space for synthesizing metal-based nanocomposites with great potential for practical application.

#### CRediT authorship contribution statement

**Liming Sun:** Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Visualization, Writing – original draft. **Xuan Wu:** Visualization. **Yubing Jiao:** Resources, Investigation, Formal analysis. **Chao Jia:** Investigation. **Tao Teng:** Investigation. **Litao Lin:** Data curation, Visualization, Software. **Fengbo Yu:** Investigation. **Zhe-lin He:** Investigation. **Jie Gao:** Investigation. **Shuwen Yan:** Resources, Investigation, Formal analysis. **Guosheng Shi:** Writing – review & editing. **Zhiyong Jason Ren:** Writing – review & editing. **Jinguang Yang:** Funding acquisition, Resources, Writing – review & editing. **Shicheng Zhang:** Resources, Supervision, Writing – review & editing. **Xiangdong Zhu:** Conceptualization, Methodology, Resources, Supervision, Funding acquisition, Writing – review & editing.

#### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data Availability

No data was used for the research described in the article.

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#### Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.apcatb.2023.123361.

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