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# Electrostatic [FeFe]-hydrogenase–carbon nitride assemblies for efficient solar hydrogen production†

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The assembly of semiconductors as light absorbers and enzymes as redox catalysts offers a promising approach for sustainable chemical synthesis driven by light. However, achieving the rational design of such semi-artificial systems requires a comprehensive understanding of the abiotic–biotic interface, which poses significant challenges. In this study, we demonstrate an electrostatic interaction strategy to interface negatively charged cyanamide modified graphitic carbon nitride ( $^{\text{NCN}}\text{CN}_x$ ) with an [FeFe]-hydrogenase possessing a positive surface charge around the distal FeS cluster responsible for electron uptake into the enzyme. The strong electrostatic attraction enables efficient solar hydrogen ( $\text{H}_2$ ) production via direct interfacial electron transfer (DET), achieving a turnover frequency (TOF) of 18 669  $\text{h}^{-1}$  (4 h) and a turnover number (TON) of 198 125 (24 h). Interfacial characterizations, including quartz crystal microbalance (QCM), photoelectrochemical impedance spectroscopy (PEIS), intensity-modulated photovoltage spectroscopy (IMVS), and transient photocurrent spectroscopy (TPC) have been conducted on the semi-artificial carbon nitride–enzyme system to provide a comprehensive understanding for the future development of photocatalytic hybrid assemblies.

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## Introduction

Converting solar energy into clean chemical fuels, such as molecular hydrogen ( $\text{H}_2$ ), holds promise for advancing the concept of a circular economy.<sup>1</sup> Among various photocatalysts, carbon nitride ( $\text{CN}_x$ ) has emerged as a particularly attractive candidate due to its unique advantages, including visible light absorption, cost-effective fabrication, scalability, and low toxicity.<sup>2</sup> To further enhance the photocatalytic performance of  $\text{CN}_x$ , significant efforts have been devoted to chemical modifications and the incorporation of co-catalysts.<sup>3</sup> The introduction of ionic cyanamide functional groups into  $\text{CN}_x$  ( $^{\text{NCN}}\text{CN}_x$ ) has demonstrated substantial improvements in charge separation and photocatalytic activity, attributed to the prolonged lifetimes of photogenerated electrons.<sup>4,5</sup> Moreover, the negatively

charged cyanamide group provides a versatile platform for potential electrostatic interactions with co-catalysts.

Nature has evolved enzymes as highly specific biological catalysts to facilitate essential processes in living organisms. Among these enzymes, hydrogenases ( $\text{H}_2$ ases) stand out for their remarkable ability to catalyze the interconversion of protons and  $\text{H}_2$  with high efficiency at near-zero overpotential under mild conditions,<sup>6</sup> surpassing the capabilities of synthetic catalysts.<sup>7</sup>  $\text{H}_2$ ases can be classified into three main types based on their metal cofactors: [NiFe]- $\text{H}_2$ ase, [FeFe]- $\text{H}_2$ ase, and [Fe]- $\text{H}_2$ ase, with [FeFe]- $\text{H}_2$ ase being generally the most active for the hydrogen evolution reaction (HER).<sup>6</sup> The extensive investigation of  $\text{H}_2$ ases as model biocatalysts<sup>8</sup> has not only inspired the design of artificial systems such as synthetic  $\text{Fe}_2\text{S}_2(\text{CO})_6$  catalysts that mimic the active site of the  $\text{Fe}_2\text{S}_2$  subunit of the [FeFe]- $\text{H}_2$ ase (Fig. S1†),<sup>9,10</sup> but also paves the way for developing bio-hybrid assemblies in semi-artificial photosynthesis systems.<sup>11,12</sup>

By interfacing  $\text{CN}_x$  with  $\text{H}_2$ ase, we combine the strengths of both artificial and biological approaches, resulting in unique properties that neither system can achieve individually.<sup>11,12</sup> This integration opens up new avenues for exploring synergistic effects and unlocking unprecedented possibilities in solar energy conversion and catalysis. The activation of [FeFe]- $\text{H}_2$ ase by light can be considered as a model for the development of efficient bio-hybrid systems. Such a photocatalytic system has thus far been demonstrated using either toxic and expensive CdTe nanocrystals<sup>13</sup> or carbon dots with a low turnover number

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(TON) of 20 000 over 24 h.<sup>14</sup> Direct electron transfer (DET) between graphitic carbon nitride (g-C<sub>3</sub>N<sub>4</sub>) and [NiFeSe]-H<sub>2</sub>ase has been established with non-specific interactions, resulting in a turnover frequency (TOF) of 4117 h<sup>-1</sup> over 4 h.<sup>15</sup> Subsequent improvements involved the incorporation of a non-diffusional electron mediator, TiO<sub>2</sub>, between g-C<sub>3</sub>N<sub>4</sub> and [NiFeSe]-H<sub>2</sub>ase, leading to an enhanced TON (4 h) of 80 000.<sup>16</sup> In addition to its application in H<sub>2</sub>ase systems, CN<sub>x</sub> has predominantly been utilized for the regeneration of NADH in mediated electron transfer (MET) processes involving formate dehydrogenase<sup>17</sup> or alcohol dehydrogenase.<sup>18</sup>

In this work, we present an approach for biological integration with CN<sub>x</sub> by demonstrating the electrostatic interaction with enzymes to form a functional biohybrid assembly. This method establishes a benchmark for solar H<sub>2</sub> production, complemented by comprehensive interfacial characterizations utilizing a quartz crystal microbalance (QCM), photoelectrochemical impedance spectroscopy (PEIS), intensity-modulated photovoltage spectroscopy (IMVS), and transient photocurrent spectroscopy (TPC). Specifically, we coupled negatively charged <sup>NCN</sup>CN<sub>x</sub> with H<sub>2</sub>ases containing different surface charges for *in vitro* photocatalytic H<sub>2</sub> production without an external electron relay. The adsorption process of H<sub>2</sub>ases on <sup>NCN</sup>CN<sub>x</sub> is quantified by QCM, whereas PEIS provides insights into the charge carrier dynamics at the biomaterial interface.

## Results and discussion

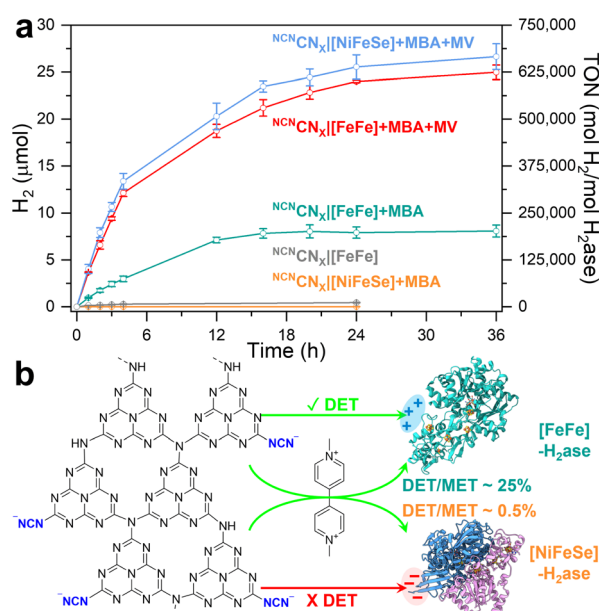
The <sup>NCN</sup>CN<sub>x</sub> photocatalysts were synthesized using melamine and potassium thiocyanate following previously published methods.<sup>4,19</sup> Detailed synthesis procedures and characterizations, including scanning electron microscopy (SEM), attenuated total reflectance Fourier-transform infrared (ATR-FTIR) spectroscopy, fluorescence spectroscopy, and ultraviolet-visible spectroscopy are provided in the ESI (Fig. S2–S5).<sup>†</sup> [FeFe]-H<sub>2</sub>ase from *Clostridium pasteurianum* (CpI, heterologously produced in *Escherichia coli*) and [NiFeSe]-H<sub>2</sub>ase from *Desulfovibrio vulgaris* Hildenborough (DvH) were expressed and purified under anaerobic conditions.<sup>20,21</sup>



**Fig. 1** Schematic of photocatalytic H<sub>2</sub> evolution coupled with alcohol oxidation to aldehyde using an electrostatic <sup>NCN</sup>CN<sub>x</sub>||[FeFe]-H<sub>2</sub>ase (CpI, PDB: 4XDC) assembly. Scale bar refers to enzyme and CN<sub>x</sub> is not shown to scale.

Fig. 1 illustrates the hypothesis that the negatively charged <sup>NCN</sup>CN<sub>x</sub> possesses the ability to activate enzymes with positively charged electron entry points, such as CpI [FeFe]-H<sub>2</sub>ase.<sup>22</sup> Additionally, the unique property of <sup>NCN</sup>CN<sub>x</sub> in converting alcohols selectively into aldehydes offers an opportunity to monitor the clean oxidation reaction of 4-methylbenzyl alcohol (4-MBA) to 4-methylbenzaldehyde (*p*-tolualdehyde), allowing the quantification of stoichiometry from the products resulting from oxidation and reduction.<sup>5,23</sup>

To construct a photocatalytic system for solar H<sub>2</sub> production coupled with selective alcohol oxidation, we interfaced [FeFe]-H<sub>2</sub>ase with <sup>NCN</sup>CN<sub>x</sub> in the presence of 50 mM 4-MBA in 1 mL aqueous MOPS buffer solution (0.1 M, pH 7). To determine the surface charge of <sup>NCN</sup>CN<sub>x</sub>, zeta potential measurements were performed. Notably, the presence of light-induced blue radicals (absorption band from 500–750 nm, Fig. S5<sup>†</sup>)<sup>5,24</sup> did not impact the surface charge of <sup>NCN</sup>CN<sub>x</sub> (Fig. S6<sup>†</sup>), indicating that these radicals are long-lived and deeply trapped photoelectrons.<sup>23,25</sup> The negatively charged surface is primarily attributed to the cyanamide group, which maintains a negative zeta potential even at a pH below 2 (Fig. S7<sup>†</sup>). CpI [FeFe]-H<sub>2</sub>ase was selected due to its distal FeS cluster ([4Fe-4S]) being surrounded by a positively charged region containing surface arginine and lysine residues. *In vivo*, this distal FeS cluster region is thought to interact with the negatively charged region of ferredoxin for electron transfer.<sup>22</sup> By constructing electrostatic <sup>NCN</sup>CN<sub>x</sub>||[FeFe]-H<sub>2</sub>ase assemblies, we achieve efficient solar H<sub>2</sub> production, with <sup>NCN</sup>CN<sub>x</sub> mimicking the role of ferredoxin to deliver electrons directly into [FeFe]-H<sub>2</sub>ase (Fig. 1).



**Fig. 2** (a) Time-dependent photocatalytic H<sub>2</sub> evolution of <sup>NCN</sup>CN<sub>x</sub> with H<sub>2</sub>ases for direct electron transfer (DET) and mediated electron transfer (MET). (b) Schematic of electron transfer process. Conditions: 1 mL anaerobic MOPS buffer (0.1 M, pH 7) containing 50 mM 4-MBA, 2 mg <sup>NCN</sup>CN<sub>x</sub>, 40 pmol H<sub>2</sub>ase (either CpI [FeFe] (PDB: 4XDC) or DvH [NiFeSe] (PDB: 5JSH)), AM 1.5G irradiation, 600 rpm stirring, 25 °C. For MET experiments, 2 mM methyl viologen (MV) was used. Error bars represent the standard deviation for a sample size of 3.



Time-dependent photocatalytic  $\text{H}_2$  evolution using  $^{\text{NCN}}\text{CN}_x\text{[FeFe]-H}_2\text{ase}$  complexes is illustrated in Fig. 2a. The TON is determined by the ratio between the number of moles of product ( $\text{H}_2$ ) and the number of moles of catalyst ( $\text{H}_2\text{ase}$ ) and the TOF is calculated by the TON per hour. Notably, a nearly linear increase in  $\text{H}_2$  yield is observed during the initial 4 h, reaching  $3.0 \pm 0.3 \mu\text{mol}$  with a TOF of  $18\,669 \text{ h}^{-1}$ . This TOF value is approximately 4.5 times higher than the previous benchmark ( $4117 \text{ h}^{-1}$ )<sup>15</sup> and is even comparable to systems utilizing MET such as  $\text{g-C}_3\text{N}_4/\text{TiO}_2$  (TOF =  $20\,000 \text{ h}^{-1}$ )<sup>16</sup> (note that previous systems used *Desulfomicrobium baculatum* (*Dmb*)  $[\text{NiFeSe}]\text{-H}_2\text{ases}$ ). Continuous irradiation of the  $^{\text{NCN}}\text{CN}_x\text{[FeFe]-H}_2\text{ase}$  assemblies for 24 h yielded  $7.9 \pm 0.6 \mu\text{mol}$  of  $\text{H}_2$  (TON = 198 125). The efficient DET between  $^{\text{NCN}}\text{CN}_x$  and  $[\text{FeFe}]\text{-H}_2\text{ase}$  can be attributed to the specific electrostatic interaction at the interface, which will be further evaluated by QCM and PEIS. Furthermore, 4-MBA was selectively oxidized to *p*-tolualdehyde (Fig. S8–S10),<sup>†</sup> with a  $\text{H}_2$ :*p*-tolualdehyde ratio of 0.77. The observed ratio indicates the deep trapping of some photo-generated electrons within the  $\text{CN}_x$  polymeric structure in addition to some buffer (MOPS) oxidation (see below).

Recent transient spectroscopic and electron paramagnetic resonance (EPR) studies extensively characterized the deep traps stored in  $^{\text{NCN}}\text{CN}_x$  on the time scale from ps to s.<sup>23–26</sup> EPR analysis showed that these long-lived and deeply trapped photoelectrons emerged as blue radicals, processing a symmetric Gaussian line near the free electron *g* value at X-band frequency of  $\sim 9.6 \text{ GHz}$ .<sup>24</sup> These blue radicals can also be visualized by UV-vis spectroscopy (Fig. S5<sup>†</sup>) and qualitatively by the eye (Fig. S11<sup>†</sup>). The oxidation ability of  $^{\text{NCN}}\text{CN}_x$  has been further evaluated using glycerol (a waste product from the biodiesel industry) as the reductant on a model  $^{\text{NCN}}\text{CN}_x/\text{Pt}$  (2 wt%) system. The oxidation products are quantified as glyceraldehyde at  $134.2 \pm 5.7 \mu\text{mol h}^{-1} \text{ g}^{-1}$  and dihydroxyacetone at  $54.9 \pm 6.8 \mu\text{mol h}^{-1} \text{ g}^{-1}$  (Fig. S12–S15)<sup>†</sup> and the  $\text{H}_2$  yield is  $94 \pm 9 \mu\text{mol h}^{-1} \text{ g}^{-1}$ . Replacing 4-MBA with ethylenediaminetetraacetic acid (EDTA) led to a  $\sim 16\%$  enhancement of  $\text{H}_2$  yield (4 h) with  $^{\text{NCN}}\text{CN}_x\text{[FeFe]-H}_2\text{ase}$  assemblies (Table S1<sup>†</sup>). This indicates that, under DET conditions, the rate of 4-MBA oxidation is limiting compared to HER. Despite this observed higher activity, it is worth noting that EDTA is considered as a sacrificial electron donor, and its oxidation results in a range of products that cannot be easily characterized. As a result, the primary focus of this study is the conversion of 4-MBA to *p*-tolualdehyde, serving as a model reaction for the selective oxidation of alcohols to aldehydes.

Exclusion controls were conducted by removing individual components from the photocatalytic system (Table S1<sup>†</sup>). As depicted in Fig. 2a and S16,<sup>†</sup> the system exhibited significantly reduced efficiency in the absence of any component, with  $\text{H}_2$  yields below  $0.3 \mu\text{mol}$  over 4 h. Minor  $\text{H}_2$  evolution activity was observed with  $^{\text{NCN}}\text{CN}_x\text{[FeFe]-H}_2\text{ase}$  assemblies even in the absence of 4-MBA, yielding  $285 \pm 24 \text{ nmol H}_2$  in 4 h. This observation suggests that MOPS serves as a much less efficient electron donor in the photocatalytic reaction. NMR analysis (Fig. S17–S20<sup>†</sup>) provides evidence of MOPS oxidation during photocatalysis. However, it is noteworthy that alcohol oxidation

on  $^{\text{NCN}}\text{CN}_x$  is so efficient and selective that the photocatalytic activity of MOPS oxidation is only  $\sim 5\%$  compared to 4-MBA oxidation in 24 h (Fig. 2a). Upon replacing MOPS buffer with pH 7 phosphate buffer, the reaction is drastically reduced in the absence of 4-MBA, accompanied by a  $\sim 27\%$  decrease in photocatalytic activity in the presence of 4-MBA (Fig. S21, Table S2<sup>†</sup>). This observation is in line with literature that MOPS as a standard Good's buffer can maintain high *in vitro* biochemical and biological activities.<sup>27</sup> Notably, control experiments were also performed to validate the proposed electrostatic interactions using a *DvH*  $[\text{NiFeSe}]\text{-H}_2\text{ase}$ , differing from the previously reported *Dmb*  $[\text{NiFeSe}]\text{-H}_2\text{ase}$ .<sup>15,16</sup> The distal FeS cluster of both  $[\text{NiFeSe}]\text{-H}_2\text{ases}$  near its surface is surrounded by amino acids that lead to a local negative charge, serving as the electron entry point for interaction with the positively charged heme of cytochrome *c*<sub>3</sub> during electron transfer *in vivo*.<sup>28</sup> Interfacing *DvH*  $[\text{NiFeSe}]\text{-H}_2\text{ase}$  with  $^{\text{NCN}}\text{CN}_x$  resulted in the production of  $8.6 \pm 0.33 \text{ nmol}$  of  $\text{H}_2$  in 4 h, with a significantly lower TON of 215 (Fig. 2a). These results indicate that electrostatic repulsion prevents DET in this system. A detailed comparison among state-of-the-art photocatalytic systems combining carbonaceous photocatalysts and  $\text{H}_2\text{ase}$  are listed in Table 1.

To determine the charge transfer efficiency of DET, methyl viologen (MV) as a soluble electron mediator is used to activate MET (Fig. 2a). Note that the presence of MV may suppress DET due to the kinetic and thermodynamic favorable one electron reduction of MV molecules to MV radicals.<sup>25,30</sup> Upon the addition of MV (2 mM), the  $\text{H}_2$  yield reaches  $24.0 \pm 0.1 \mu\text{mol}$  for *CpI*  $[\text{FeFe}]\text{-H}_2\text{ase}$  and  $25.6 \pm 1.3 \mu\text{mol}$  for *DvH*  $[\text{NiFeSe}]\text{-H}_2\text{ase}$  after 24 h of irradiation. The comparable  $\text{H}_2$  yields, despite differences in specific activity, indicate that the rate limiting step during MET is not enzyme turnover but the photoactivity of  $^{\text{NCN}}\text{CN}_x$ , as evidenced by control experiments (Table S1<sup>†</sup>). Specifically, by doubling the  $\text{H}_2\text{ase}$  loading from 40 pmol to 80 pmol, no significant changes in  $\text{H}_2$  yields were observed over

**Table 1** State-of-the-art photocatalytic systems combining carbonaceous light absorbers and  $\text{H}_2\text{ases}$

Photocatalytic system (DET)	TOF <sup>a</sup> ( $\text{h}^{-1}$ )	TON <sup>b</sup>	AQE	Ref.
$^{\text{NCN}}\text{CN}_x\text{[FeFe]} + \text{MBA}^d$	18 669	198 125	0.35%	This work
$\text{g-C}_3\text{N}_4\text{[NiFeSe]} + \text{EDTA}^d$	4117	36 000	0.07%	15
$\text{CDs[NiFeSe]} + \text{EDTA}^d$	3125	44 000	0.36%	29
$\text{CDs[FeFe]} + \text{TEOA}^e$	1500	19 000	1.7%	14
Photocatalytic system (MET)	TOF <sup>a</sup> ( $\text{h}^{-1}$ )	TON <sup>b</sup>	AQE	Ref.
$^{\text{NCN}}\text{CN}_x\text{[FeFe]} + \text{MBA} + \text{MV}^d$	75 769	600 350	1.4%	This work
$^{\text{NCN}}\text{CN}_x\text{[NiFeSe]} + \text{MBA} + \text{MV}^d$	83 588	638 825	N.A.	This work
$\text{g-C}_3\text{N}_4/\text{TiO}_2\text{[NiFeSe]} + \text{EDTA}^{c,d}$	20 000	275 000	0.51%	16
$\text{CDs[FeFe]} + \text{TEOA} + \text{MV}^e$	2000	32 000	N.A.	14

<sup>a</sup> TOF is calculated from 4 h photocatalysis. <sup>b</sup> TON is calculated from 24 h photocatalysis. <sup>c</sup>  $\text{TiO}_2$  as a non-diffusional electron mediator. Illumination conditions. <sup>d</sup> AM 1.5G, 100  $\text{mW cm}^{-2}$ , Xe lamp. <sup>e</sup> 50  $\text{mW cm}^{-2}$ , LED lamp.





both 4 hour and 24 hour periods under MET conditions. The efficiency of DET is qualitatively determined by the DET : MET ratio, defined by the ratio of  $H_2$  yield in the absence of MV (DET) and in the presence of MV (MET). In the case of [FeFe]- $H_2$ ase and [NiFeSe]- $H_2$ ase, DET : MET ratios of approximately 25% and 0.5% are observed, respectively (Fig. S22†). By comparing the results obtained from DET and MET, a schematic representation can be depicted in Fig. 2b. It highlights the establishment of efficient electron transfer directly between  $^{NCN}CN_X$  and [FeFe]- $H_2$ ase, with a DET : MET ratio of 25%. This finding emphasizes the effectiveness and benefits of electrostatic interactions in facilitating DET. Conversely, the electrostatic repulsion between [NiFeSe]- $H_2$ ase and  $^{NCN}CN_X$  prevents DET, resulting in a low DET : MET ratio of 0.5%. Notably, the apparent quantum efficiency (AQE) measured at 450 nm with  $^{NCN}CN_X$ [FeFe]- $H_2$ ase assemblies under DET and MET conditions are 0.35% and 1.4% (Table S3†), respectively. In contrast, a model  $^{NCN}CN_X$ /Pt (2 wt%) system yields  $0.28 \pm 0.05 \text{ mmol h}^{-1} \text{ g}^{-1} H_2$  and  $0.51 \pm 0.09 \text{ mmol h}^{-1} \text{ g}^{-1}$  *p*-tolualdehyde with an AQE of 1.92% at 450 nm. In terms of the overall stability of the designed systems, the DET system exhibited a rather linear photocatalytic activity up to 12 h. While MET systems are fully inactive only after 20 h. Long-term experiments up to 36 h confirmed these trends, with no further  $H_2$  production in DET after 24 h and minimal  $H_2$  yield increases in MET (24.0 to 25.0  $\mu\text{mol}$  for [FeFe] and 25.6 to 26.7  $\mu\text{mol}$  for [NiFeSe]). These findings align with recent observations on carbon dot/[FeFe]- $H_2$ ase photocatalytic systems.<sup>14</sup>

To gain deep insights into the interaction between  $^{NCN}CN_X$  and  $H_2$ ase, QCM analysis was conducted. As shown in the schematic in Fig. 3a, the Au-coated quartz chip was functionalized with a thin layer of  $^{NCN}CN_X$  by drop casting 0.5 mL of an ultrasonicated suspension ( $0.1 \text{ mg mL}^{-1}$ ) of  $^{NCN}CN_X$ , to mimic the operando conditions during photocatalysis. By flowing a buffer solution containing enzymes on the chip, the adsorption process of  $H_2$ ase at the surface of  $^{NCN}CN_X$  can be monitored as a function of time and quantified based on the Sauerbrey equation.<sup>31</sup> Fig. 3b shows the QCM analysis of *Cpl* [FeFe]- $H_2$ ase and *DvH* [NiFeSe]- $H_2$ ase on the  $^{NCN}CN_X$ -modified chip. After establishing a stable baseline by circulating 0.1 M MOPS pH 7 buffer with 50 mM 4-MBA, the enzymes were introduced separately at the same concentration as in the photocatalysis

experiments. The adsorption of both  $H_2$ ases on  $^{NCN}CN_X$  exhibits in two distinct stages, a fast adsorption process before 1.5 h and slow adsorption after 1.5 h. Interestingly, a higher amount of [NiFeSe]- $H_2$ ase ( $39.5 \text{ pmol cm}^{-2}$ ) is adsorbed onto  $^{NCN}CN_X$  compared to [FeFe]- $H_2$ ase ( $16.6 \text{ pmol cm}^{-2}$ ) over 10 h. The observed adsorption profiles can be explained by the proposed electrostatic interactions in Fig. 3c. Based on the electrostatic potential maps (Fig. 3c), both  $H_2$ ases exhibit distinct surface charge distribution. By indexing the specific protein structures, *Cpl* [FeFe]- $H_2$ ase (PDB: 4XDC), and *DvH* [NiFeSe]- $H_2$ ase (PDB: 5JSH), within the protein dipole moment database,<sup>32</sup> it is found that [NiFeSe]- $H_2$ ase possesses a larger dipole moment of 1972 D compared to [FeFe]- $H_2$ ase (1707 D), resulting in a stronger association (Fig. 3b). However, for [NiFeSe]- $H_2$ ase, DET can only be established *via* the negatively charged patch near the distal FeS cluster, which is unfavorable for the negatively charged  $^{NCN}CN_X$  and thus dramatically reduces DET to the enzyme active site for catalysis. Consequently, the strong association observed at the  $^{NCN}CN_X$ [NiFeSe]- $H_2$ ase interface is non-specific and results mainly in inactive biohybrid assemblies. In contrast, adsorbed [FeFe]- $H_2$ ase has positively charged distal FeS cluster that can specifically interact with negatively charged  $^{NCN}CN_X$  for DET.<sup>22,28</sup> The presence of other positively charged regions in the [FeFe]- $H_2$ ase (Fig. 3c) might also attract  $^{NCN}CN_X$ . However, due to the rigidity of the heptazine-based  $^{NCN}CN_X$  (A-B' stacking), proper orientation for DET near the distal FeS cluster could be hindered. This might explain the observed relatively low 25% DET/MET ratio. Therefore, QCM analysis provides valuable insights into the significance of specific interactions in facilitating DET.<sup>33</sup>

To investigate the charge carrier dynamics between  $H_2$ ases and  $^{NCN}CN_X$ , PEIS was performed using a three-electrode configuration. By applying a sinusoidal potential modulation to the  $^{NCN}CN_X$ -modified working electrode, which was made by depositing a  $^{NCN}CN_X$  suspension ( $5 \mu\text{L}$ ,  $24 \text{ mg mL}^{-1}$ ) on FTO-coated glass,<sup>23</sup> the impedance was recorded as the ratio of the complex-valued potential and current.<sup>34</sup> A Randles circuit consisting of a series resistance ( $R_s$ ) in parallel with a combination of bulk capacitance ( $C_{\text{bulk}}$ ) and charge transfer resistance ( $R_{\text{ct}}$ ), was proposed to fit the impedance response (Fig. 4a).<sup>35</sup> The Nyquist plot (Fig. 4a) of the impedance response measured at  $-0.1 \text{ V}$  vs. the reversible hydrogen electrode (RHE), is



**Fig. 3** (a) Schematic illustration of a  $^{NCN}CN_X$ -coated quartz chip. Buffer containing [FeFe]- $H_2$ ase (PDB: 4XDC) is flowing towards the chip and [FeFe]- $H_2$ ase is adsorbed onto the surface. (b) QCM analysis of the adsorption process of  $H_2$ ase on a  $^{NCN}CN_X$ -coated quartz chip. Conditions: 2 mL anaerobic MOPS buffer (0.1 M, pH 7) containing 50 mM 4-MBA, 80 pmol  $H_2$ ase (either *Cpl* [FeFe] or *DvH* [NiFeSe]), 25 °C. (c) Electrostatic potential maps of *Cpl* [FeFe] (PDB: 4XDC) and *DvH* [NiFeSe] (PDB: 5JSH), and their interactions with  $^{NCN}CN_X$ .



Fig. 4 (a) Nyquist plots and (b) Bode phase plots of PEIS signal (open circles) with corresponding fitting curves (solid lines). Inset: proposed equivalent circuit to fit the impedance response. Conditions: 20 mL anaerobic MOPS buffer (0.1 M, pH 7) containing 50 mM 4-MBA, Ag/AgCl (3 M NaCl) reference electrode, Pt mesh counter electrode, AM 1.5G irradiation, 25 °C.

dominated by a single semicircle with no indication of a Warburg diffusion element. The proposed equivalent circuit provided a good fit ( $r^2 > 0.95$ ) to the impedance response, enabling quantitative analysis of the charge transfer process.

Upon introduction of [FeFe]-H<sub>2</sub>ase on the working electrode, a decrease in the semicircle diameter is observed, corresponding to a decrease in  $R_{ct}$  from 15 975  $\Omega$  to 12 317  $\Omega$ . This indicates that [FeFe]-H<sub>2</sub>ase, as a biocatalyst, facilitates the charge transfer from  $^{NCN}CN_X$  to the electrolyte for HER. Likewise,  $^{NCN}CN_X$ [NiFeSe]-H<sub>2</sub>ase shows a  $R_{ct}$  of 13 950  $\Omega$ , similar to the bare  $^{NCN}CN_X$ . Such behaviors have been widely observed when incorporating synthetic co-catalysts onto semiconductors.<sup>36</sup> The fitting results allowed determination of the pseudo first-order rate constant for charge transfer ( $k_{ct}$ ), based on the phenomenological model developed for an illuminated photoelectrode.<sup>37,38</sup> Specifically, the angular frequency at the maximum imaginary component of the semicircle in Nyquist plot (Fig. 4a) is equal to  $k_{ct}$ . The addition of [FeFe]-H<sub>2</sub>ase significantly enhances  $k_{ct}$  from 6.85 s<sup>-1</sup> to 11.99 s<sup>-1</sup>, whereas [NiFeSe]-H<sub>2</sub>ase shows a negative impact on  $k_{ct}$  with a value of 5.02 s<sup>-1</sup>, further confirming the importance of specific interactions in facilitating the charge transfer process. The Bode phase plots (Fig. 4b) revealed that the charge transfer process occurred within the frequency range of 0.1 Hz to 1 kHz, consistent with the reported timeframe for photocatalytic HER using  $CN_X$ .<sup>36</sup> Within this range, the characteristic frequency at the maximum phase shift of  $^{NCN}CN_X$ [FeFe]-H<sub>2</sub>ase are higher than  $^{NCN}CN_X$ [NiFeSe]-H<sub>2</sub>ase and pristine  $^{NCN}CN_X$ , indicating [FeFe]-H<sub>2</sub>ase can initiate a faster charge transfer process for HER. Likewise, the characteristic frequencies of  $^{NCN}CN_X$ [NiFeSe]-H<sub>2</sub>ase and pristine  $^{NCN}CN_X$  remain the same, meaning that DET cannot be established between  $^{NCN}CN_X$  and [NiFeSe]-H<sub>2</sub>ase. The voltage-dependent impedance response is illustrated in Fig. S23.† A more negative applied potential yields a diminished semicircular feature in the Nyquist plots, indicating reduced charge transfer resistance. This observation arises from the introduction of a larger band bending, resulting in improved separation of photogenerated charges.<sup>39,40</sup> Consequently, a greater population of free charge carriers is localized

within the semiconductor, increasing the conductivity of  $^{NCN}CN_X$ . Notably, the RC response of the conductive substrate forms a semicircle with a diameter of approximately 200  $\Omega$  in the Nyquist plots (Fig. S24a†) at high frequency region (10 kHz to 1 MHz, Fig. S24b†) in the Bode phase plots.<sup>23</sup> This impedance study on  $CN_X$  with H<sub>2</sub>ase demonstrates that a specific interaction enables efficient DET by decreasing in  $R_{ct}$  and increasing in  $k_{ct}$ .

The charge carrier dynamics between H<sub>2</sub>ases and  $^{NCN}CN_X$  were further examined using IMVS and TPC techniques in a three-electrode setup. IMVS is a spectroelectrochemical method widely employed in assessing electron recombination processes in photovoltaics. It monitors the open circuit voltage response to the sinusoidally modulated incident light intensity. The characteristic frequency observed at the minimum point of the Nyquist plot ( $f_{min}$ ) directly correlates to the time constant of electron recombination. This parameter can be calculated using the following equation, providing the first-order electron lifetime  $\tau_n$ :<sup>41</sup>

$$\tau_n = (2\pi f_{min})^{-1}$$

This model has been recently expanded to photoanodes for solar water oxidation.<sup>42,43</sup> Although IMVS is not *operando* due to the distinct differences between a photoelectrode and a photocatalyst, photoelectrochemical techniques have been widely employed to gain insights into charge carrier behaviors in photochemical systems. This equation can be applied to a  $^{NCN}CN_X$ -based photoelectrode due to it functions as a photoanode in the presence of 4-MBA and under open circuit conditions.<sup>23</sup> As depicted in Fig. 5a, the IMVS response exhibits a distinct semicircle in quadrant IV of the Nyquist plot, suggesting rapid kinetics in 4-MBA oxidation, similar to the cases of sacrificial Na<sub>2</sub>SO<sub>3</sub> and H<sub>2</sub>O<sub>2</sub> oxidation on a hematite photoanode.<sup>42,43</sup>

The non-specific interaction between [NiFeSe]-H<sub>2</sub>ase and  $^{NCN}CN_X$  yields  $\tau_n$  of 57.0  $\mu$ s, whereas 55.1  $\mu$ s is observed for pristine  $^{NCN}CN_X$ . This consistency indicates that the charge recombination process remains unaffected, matching with our



Fig. 5 (a) Nyquist plots of IMVS response. (b) Normalized TPC response with corresponding exponential fitting curves. Conditions: 20 mL anaerobic MOPS buffer (0.1 M, pH 7) containing 50 mM 4-MBA, Ag/AgCl (3 M NaCl) reference electrode, Pt mesh counter electrode, AM 1.5G irradiation, 25 °C.



previous observations of the absence of DET between [NiFeSe]-H<sub>2</sub>ase and <sup>NCN</sup>CN<sub>X</sub>. Upon the introduction of [FeFe]-H<sub>2</sub>ase onto <sup>NCN</sup>CN<sub>X</sub>, we observe a prolonged  $\tau_n$  of 81.6  $\mu$ s that can be explained as follows: Even under open circuit conditions, where no net electron exchange occurs at the <sup>NCN</sup>CN<sub>X</sub>|electrolyte interface, photogenerated electrons theoretically have the potential to react with protons *via* H<sub>2</sub>ases. Note that a TOF of 18 669 h<sup>-1</sup> (<sup>NCN</sup>CN<sub>X</sub>|[FeFe]-H<sub>2</sub>ase) corresponds to a frequency of 5.2 Hz. Therefore, all losses of photogenerated electrons within the measured frequency range (0.5 MHz to 0.5 Hz) are a combination of bulk recombination and catalytic reaction. The influence of a catalytic overlayer on IMVS response remains a topic of debate. Recent studies indicate that a co-catalyst overlayer can delocalize photogenerated charge carriers from the bulk photoelectrode, promoting charge separation and prolonging electron lifetime.<sup>42</sup> Here, despite the absence of net exchange current, we hypothesize that photogenerated electrons can be stored in H<sub>2</sub>ase in the form of metal hydrides and reduced FeS clusters,<sup>44</sup> *i.e.*, reversible intermediates for H<sub>2</sub> evolution reaction. This storage mechanism reduces the probability of charge recombination with holes, resulting in an extended electron lifetime. IMVS observations are in line with the recent transient spectroscopic study on the impact of electron accumulation to charge recombination in <sup>NCN</sup>CN<sub>X</sub>.<sup>25</sup> Thus, we demonstrate the use of IMVS on carbon nitride materials and on studying bio-hybrids.

Having gained insights into charge recombination, we conducted TPC measurements to assess the influence of H<sub>2</sub>ases on the electron extraction process of <sup>NCN</sup>CN<sub>X</sub>. The normalized TPC response, illustrated in Fig. 5b, reveals that the integration of [FeFe]-H<sub>2</sub>ase with <sup>NCN</sup>CN<sub>X</sub> leads to a significant reduction in electron transit time ( $\tau_t$ ) from 0.28 s to 0.16 s. This indicates that [FeFe]-H<sub>2</sub>ase, acting as a co-catalyst for <sup>NCN</sup>CN<sub>X</sub>, can effectively collect photoelectrons for HER, thereby facilitating electron transport within <sup>NCN</sup>CN<sub>X</sub>.<sup>45,46</sup> Likewise, <sup>NCN</sup>CN<sub>X</sub>|[NiFeSe]-H<sub>2</sub>ase assemblies are non-specific, resulting in an unchanged  $\tau_t$  of 0.30 s. The combined results from IMVS and TPC highlight the favorable effects of DET between [FeFe]-H<sub>2</sub>ase and <sup>NCN</sup>CN<sub>X</sub> on both charge recombination and transport. In contrast, the non-specifically interacted <sup>NCN</sup>CN<sub>X</sub>|[NiFeSe]-H<sub>2</sub>ase assemblies demonstrate minimal alterations in both  $\tau_n$  and  $\tau_t$ .

## Conclusions

We present an electrostatic strategy for linking enzymes with carbon nitrides, demonstrating a benchmark for DET between <sup>NCN</sup>CN<sub>X</sub> and [FeFe]-H<sub>2</sub>ase for solar H<sub>2</sub> production with a TON of  $2 \times 10^5$  and a DET/MET ratio of 25% over 24 h. In contrast, the electrostatic repulsion between [NiFeSe]-H<sub>2</sub>ase and <sup>NCN</sup>CN<sub>X</sub> drastically reduced DET, leading to a DET/MET ratio of 0.5%. QCM analysis demonstrates that specific interactions play a pivotal role in enabling DET, irrespective of the observed differences in the adsorption profiles. Complementary spectroelectrochemical analysis using PEIS, IMVS, and TPC show that interfacing [FeFe]-H<sub>2</sub>ase with <sup>NCN</sup>CN<sub>X</sub> facilitates charge transfer and suppresses charge recombination, as evidenced by a 23% less resistive  $R_{ct}$ , a 75% faster  $k_{ct}$ , a 48% longer  $\tau_n$ , and

a 43% shorter  $\tau_t$  than bare <sup>NCN</sup>CN<sub>X</sub>. This study provides a promising and straightforward approach for achieving efficient electron transfer between carbon nitride and enzymes and serves as a reference for studying the charge carrier behavior of enzyme-photocatalyst assemblies using interfacial characterizations.

## Data availability

Data supporting the findings of this study are available from the Cambridge data repository: <https://doi.org/10.17863/CAM.106936>.

## Author contributions

Yongpeng Liu conceptualization, data curation, software, formal analysis, funding acquisition, investigation, visualization, methodology, writing – original draft, project administration, writing – review & editing; Carolina Pulignani conceptualization, resources, data curation, formal analysis, investigation, visualization, methodology, writing – original draft, writing – review & editing; Sophie Webb resources, investigation, methodology, writing – review & editing; Samuel J. Cobb data curation, investigation, methodology, writing – review & editing; Santiago Rodríguez-Jiménez formal analysis, investigation, methodology, writing – review & editing; Dongseok Kim investigation, methodology; Ross D. Milton conceptualization, resources, supervision, funding acquisition, validation, writing – original draft, project administration, writing – review & editing; Erwin Reisner conceptualization, resources, formal analysis, supervision, funding acquisition, validation, investigation, visualization, writing – original draft, project administration, writing – review & editing.

## Conflicts of interest

There are no conflicts to declare.

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