

ARTICLE

Covalent Triazine Framework/Carbon Nanotube Hybrids: a Novel Class of Metal-free Electrocatalysts for the Reduction of CO₂

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Electrochemical reduction of CO₂ provides a way to generate base chemicals from an abundant C1-source under mild conditions, whilst at the same time mitigating CO₂ emissions. In this work, a novel class of tailorable, porous metal-free electrocatalysts for this process is proposed. Covalent triazine frameworks (CTFs) are grown in situ onto functionalized multiwalled carbon nanotubes. The hydroxyl groups decorating the surface of the multiwalled carbon nanotubes facilitate intimate contact between the carbon nanotubes and CTF, thus promoting efficient electron transfer. The novel hybrid materials generate CO with a Faradaic efficiency up to 81% at an overpotential of 380 mV. The selectivity of the electrocatalysts could be linked to the amount of nitrogen present within the framework.

Introduction

Global warming, caused by anthropogenic CO₂ emission, is without doubt one of the greatest challenges in this century. Despite the increased awareness and efforts so far, the total worldwide anthropogenic CO₂ emissions keep on rising – in 2018 an all-time-high of 37.1 billion metric tonnes of CO₂ was emitted¹. Carbon capture and utilisation (CCU), i.e. the collection and subsequent conversion of CO₂ into valuable compounds, is expected to become an important mitigation strategy in the near future. Several methods for the conversion of CO₂ are currently under investigation, including biochemical, thermochemical, photochemical and electrochemical routes². In particular electrochemical reduction has been recognized as an efficient and scalable method capable of generating several base chemicals, including carbon monoxide, formic acid and methane from CO₂³. It is an appealing strategy because of several reasons⁴. First of all, the reactions can be conducted in

aqueous media, which is a cheap, abundant and environmentally friendly way to facilitate the proton and electron transfer steps – although alternative electrolytes are being researched as well⁵. Furthermore, the reaction can be performed under atmospheric pressure and at room temperature. By changing the reaction parameters such as the applied potential, electrolyte, electrocatalyst or pH, one can tune the product selectivity towards a desired endproduct and ensure a minimum of by-product formation. Finally, the electricity necessary to drive the reaction can be produced in a renewable manner by e.g. solar power or wind turbines. A widespread industrial implementation however has so far not been realized. To achieve this, improvement of the catalyst cost, current density, overpotential and stability will be necessary^{6–8}. The traditional (noble) metal-based catalysts are often expensive or suffer from a poor selectivity due to the competitive and kinetically favoured H₂ evolution side reaction, low electrochemical stability or need for high overpotentials^{4,9,10}. To overcome these shortcomings, a new generation of metal-free electrocatalysts has recently been described, of which the majority is based on nitrogen-doped carbons. Promising findings have been reported proving metal-free catalysts can indeed compete with and in some cases even outperform their metal-based rivals^{11–16}. A good catalyst should exhibit a high and stable current density at a low overpotential, combined with excellent selectivity towards one specific endproduct.

The use of covalent organic frameworks (COFs) as suitable candidates for the metal-free electrocatalytic reduction of CO₂ is introduced. COFs are isorecticular porous networks consisting entirely of light elements linked via a reversible covalent reaction³. The chemical properties of the framework depend on the applied monomer and linkage motif, and can be further altered by post-synthetic modifications. Due to their intrinsic porosity, exceptional surface area (up to 4200 m²/g), well-

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defined structure and high modularity, COFs find application in a wide range of fields, including adsorption, gas separation and heterogeneous catalysis¹⁷. In the context of electrocatalytic CO₂ reduction, our interest went in particular to a specific subclass of COFs, denoted as covalent triazine frameworks (CTFs). Based on the stable triazine ring as linkage unit, CTFs exhibit excellent thermal and (electro)chemical stability and can be synthesised in a convenient and straightforward manner. This triazine linkage results in an inherent high amount of nitrogen present within the CTF structure. Through a rational selection of the monomer, the nitrogen content can be even further increased, or another heteroatom can be introduced. This co-doping of nitrogen-doped carbons with elements such as sulphur, fluorine or boron has indeed proven to ameliorate catalytic performance^{18,19}. The customary ionothermal synthesis of CTFs was developed in 2008 by Kuhn et al.²⁰ and relies on the trimerisation of nitrile-containing monomers at elevated temperatures (> 400°C) in the presence of ZnCl₂ as a Lewis acid catalyst. This method yields stable, but amorphous materials, with partial carbonization and irreversible C-N bond formation due to the applied harsh synthesis conditions²¹. The significant amount of defects present in this material and the low degree of crystallinity result into a poor electrical conductivity. For this reason, most reports of CTFs in electrocatalysis describe metallated CTFs, in which the framework acts as a support for the catalytically active metal particles or atoms. Within this context Su et al. reported in 2018 on a pyridine-based CTF decorated with Co or Ni atoms²². Carbon black was added during the synthesis to further improve the electrical conductivity. While the Co- and Ni-decorated CTFs indeed showed appreciable activity (a current density of -1mA/cm², 90% Faradaic efficiency (FE) for CO at -0.8V vs. RHE for a nickel-decorated CTF), the pristine pyridine CTF exhibited negligible CO generation (> -0.05 mA/cm², < 5 % FE for CO at -0.8V vs. RHE). In a related work reported by Lu et al. in 2019, Ni was anchored onto a porphyrin-based CTF. The metal-containing CTF favoured the reduction of CO₂ to CO with an excellent FE of 97%. A current density of -52.9mA/cm² was achieved using a reasonably high electrode potential of -0.9V, but the activity of the bare CTF was negligible²³. Zhu et al. were able to significantly increase the performance of the pyridine-CTF by performing the synthesis at 600°C, effectively pyrolyzing the CTF²⁴. This improvement however comes at the cost further disordering of the material, to the point where it can hardly be called a CTF anymore. Note that the material was also mixed post-synthetically with carbon black to improve the overall conductivity of the catalytic surface. To the best of our knowledge, the only report of a successful metal-free CTF for the electrocatalytic reduction of CO₂ was reported in 2018 by Wang et al.²⁵. Their tetrafluoroteraphtalonitrile-based CTF was made at 400°C and generated methane with an impressive FE of 99.4% at a low electrode potential (ca. -0.8 V vs RHE). They also reported that the synthesis at higher temperatures (up to 900°) resulted into materials with an improved current density, accompanied with a severe loss of the fluorine content during the synthesis. However, it is important to note here that for

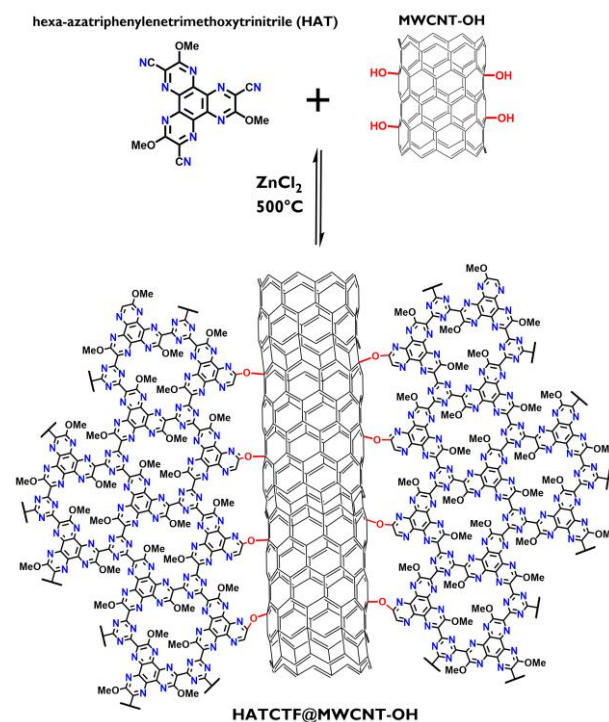


Figure 1: Idealized structure of HATCTF@MWCNT-OH

none of their materials the current density exceeded -0.4 mA/cm² in the range of -0.4 V to -1.2 V versus RHE.

In this work a novel approach is introduced to overcome the conductivity issue of CTFs by constructing hybrid nanostructures, in which the N-rich CTF will function as the active sites, while the high electrical conductivity will be assured by the functionalized multiwalled carbon nanotubes (MWCNTs) on which the CTFs will be grown onto [Fig. 1]. The surface of the multiwalled nanotubes was modified with hydroxyl groups to facilitate the growth of the CTF onto the nanotube and strengthen the contact between both materials, thus improving electron transfer.

Experimental section

Synthesis of the MWCNT-OH material

The MWCNTs were obtained from Nanocyl SA and used without further purification. For the functionalization of the nanotubes, 1g of the MWCNT was refluxed for 24 hours at 120°C in a 5M nitric acid solution. The product was filtered through a PTFE membrane (0.45 mm), washed with water until the filtrate was pH-neutral, and dried overnight under vacuum. Afterwards, the MWCNT-COOH-OH material was dispersed in 100 mL methanol in a round bottom flask and placed in an ice bath. 5 g of sodium borohydride was added slowly under continuous stirring. After stirring for 24 hours, the product was filtered through a PTFE membrane (0.45 mm), washed with water until the filtrate was pH-neutral, and dried overnight under vacuum [Fig. S1].

Synthesis of the hexa-azatrimethoxytrinitrile (HAT) monomer

In a first step, hexa-azatriphenylenehexacarbonitrile, HAT-(CN)₆ was synthesized according to the published procedure of Czarnik et al.^{26,27} For the synthesis of HAT-(CN)₆, hexaketocyclohexane octahydrate (4 g, 12.6 mmol) and diaminomaleonitrile (10.88 g, 100.8 mmol) were refluxed in acetic acid (AcOH, 150 mL) for 2 h. The black suspension was filtered off while hot and washed with hot AcOH (3 × 25 mL) resulting in a black solid. The solid was suspended in 30 % HNO₃ (60 mL) and heated at 100 °C for 3 h. The hot dark brown suspension was poured into ice water (200 mL) and cooled overnight. The suspension was filtered and the solid was refluxed in CH₃CN (400 mL) for 2 h and was filtered. The filtrate was evaporated under vacuum to give an orange solid (2.4 g, yield 50 %). In the following step the HAT-(CN)₆ (700 mg) was dissolved in CH₃CN (40 mL) followed by the addition of 30 mL CH₃OH, as reported by Chang et al.²⁸ The reaction mixture was refluxed for 50 hours at 85 °C, and left to stand overnight at room temperature. The formed yellow precipitate was filtered. A further crop of product was obtained by adding a few drops of NaOMe to the collected filtrate, until a new precipitation started. The solution was left to stand for an additional 48 hours to precipitate further. The precipitate was filtered, washed extensively with methanol and water, and dried under vacuum overnight. The structure was confirmed using ¹H NMR [Fig. S2].

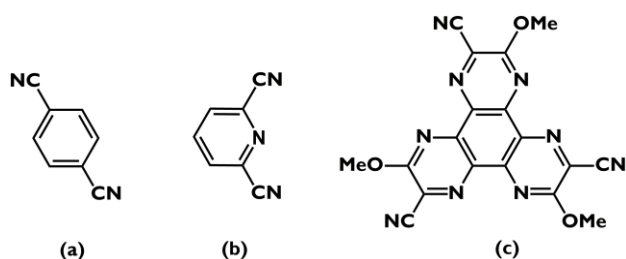


Figure 2: The applied monomers: (a) terephthalonitrile, (b) pyridine-2,6-dicarbonitrile and (c) hexa-azatriphenylenehexacarbonitrile for the synthesis of the corresponding hybrid materials CTF1@MWCNT-OH, pyCTF@MWCNT-OH and HATCTF@MWCNT-OH.

Synthesis of the CTF@MWCNT-OH hybrid materials

The monomers (terephthalonitrile (A), pyridine-2,6-dicarbonitrile (B) or hexa-azatriphenylenehexacarbonitrile (HAT) (C), [Fig. 2] were thoroughly ground in a mortar in the presence of a twofold mass amount of MWCNT-OH [Table 1]. Hereafter, the solid mixture was placed in a glass ampoule, together with an appropriate amount of ZnCl₂. Prior to use, the ZnCl₂ catalyst was dried at 120 °C under vacuum for at least 24 hours. In the following, the ampoule was degassed for at least 4 hours, and flame-sealed. For the monomers terephthalonitrile and hexa-azatriphenylenehexacarbonitrile a 5:1 molar ratio of ZnCl₂ to monomer was used, while for the pyridine-2,6-dicarbonitrile monomer a 10:1 molar ratio was applied as no surface area was obtained for the latter material when a 5:1 molar ratio was used [Table 1, Fig. S3]. The glass ampoules were heated to 500 °C (for the pyCTF@MWCNT-OH and HATCTF@MWCNT-OH material) or to 400 °C (for the CTF1@MWCNT-OH), and kept at this temperature during 48 hours before cooling down. Afterwards, the glass ampoules were opened, and the obtained black solids were refluxed in 1M HCl at 110 °C to remove residual ZnCl₂. After

Table 1 - An overview of the synthesized hybrid materials under different reaction conditions

Sample	CTF1@ MWCNT-OH	pyCTF@ MWCNT-OH	HATCTF@ MWCNT-OH
Monomer	A*	B*	C*
Amount (mg)	37,5	37,5	33
MWCNT-OH (mg)	75	75	66
ZnCl ₂ ratio	5:1	10:1	5:1
ZnCl ₂ (mg)	198	395	56
Temperature (° C)	400	500	500

*A: terephthalonitrile, B: pyridine-2,6-dicarbonitrile, C: hexa-azatriphenylenehexacarbonitrile

24 hours, the solids were filtered through a PTFE membrane (0.45 mm), and washed with water until the filtrate was pH-neutral. Finally, the hybrid materials were stirred for 24 hours in THF at room temperature, filtered through a PTFE membrane (0.45 mm), washed with THF and acetone, and afterwards dried overnight under vacuum.

Characterization

Nitrogen sorption analysis was conducted at 77 K using an automated gas sorption system Belsorp-Mini II gas analyzer. Prior to the sorption measurements, the samples were dried under vacuum at 120 °C overnight to remove adsorbed water. Specific surface areas were calculated based on Brunauer–Emmett–Teller (BET) analysis. Total pore size was calculated based on Barrett–Joyner–Halenda (BJH) analysis. Elemental analysis was measured on a Thermo Scientific Flash 2000 CHNS-O analyzer equipped with a TCD detector. Powder X-ray diffraction (PXRD) patterns were collected on a Thermo Scientific ARL X'Tra diffractometer, operated at 40 kV, 40 mA using Cu-Kα radiation (1.540 Å). X-ray photoelectron spectroscopy (XPS) measurements were performed on a Thermo Fisher Scientific Escalab 250 Xi. Annular dark field scanning transmission electron microscopy (ADF-STEM) and energy dispersive X-Ray (EDX) spectroscopy experiments were carried out using a FEI Titan transmission electron microscope operated at an accelerating voltage of 200 kV and equipped with a probe spherical aberration corrector unit and a Super-X EDX system²⁹. The samples were prepared by dispersing powder samples in ethanol and dropping the dispersion onto a carbon coated TEM copper grid.

Electrochemical tests

The electrochemical performance of the different CTF@MWCNT-OH materials was examined in a gas tight electrochemical cell (H-type configuration), featuring two compartments, divided by a proton-permeable Nafion 117 membrane [Fig. S4]. The cathodic chamber with the glassy carbon working electrode (WE) was filled with 0.1 M KHCO₃, saturated with CO₂ (pH = 6.70) in the presence of the Ag/AgCl reference electrode. The anodic chamber was filled with an unsaturated 0.1 M KHCO₃ solution in the presence of a platinum counter electrode. The cell was kept at a constant temperature of 18 °C by means of water cooling. The WE, counter electrode and reference electrode were coupled to a PARSTAT 4000 potentiostat while the cell headspace was connected to a Thermo-Fisher Scientific TRACE™ 1300 Gas Chromatograph

equipped with a TCD detector. The WE consisted of a glassy carbon rod with a base of 0.2 cm², embedded in epoxy in such a way that only the ground plane is available for reaction. The surface was mechanically polished using alumina particles slurry before every reaction to a roughness of 0.05 μm. For each hybrid material, a catalyst ink was prepared, which consisted of 2 mg CTF@MWCNT-OH, 195 μl isopropanol, and 5 μl Nafion® 117 solution (5 wt% in a mixture of lower alcohols). This ink was sonicated for at least one hour to obtain a good dispersion before usage. 20 μl of the ink was dropcasted onto the glassy carbon electrode surface of 0.2 cm² in four steps of 5 μl, resulting in a catalyst loading of ca. 1 mg/cm². After coating, the electrode was dried overnight in a closed container before usage.

Results and discussion

To ensure intimate contact between the CTF materials and the MWCNT, hydroxyl functionalities were introduced on the surface of the carbon nanotubes, leading to hydroxyl-functionalized multiwalled carbon nanotubes (MWCNT-OH). This functionalization was achieved by acidic oxidation in a HNO₃ solution according to the reported recipe of Abednatanzi et al.³⁰. By applying this method, a variety of oxygen-containing species were introduced onto the surface of the nanotube, the majority being carboxyl- and hydroxyl. A subsequent chemical reduction with NaBH₄ aimed to convert these carboxyl-groups into hydroxyl groups. A broad O-H stretching band around 3000–3500 cm⁻¹, a C=O stretching vibration around 1720 cm⁻¹, a small O-H bending peak at 1455 cm⁻¹, a C=C stretching around 1570 cm⁻¹ and a C-H in-plane bending at 1380 cm⁻¹ were observed in the FTIR spectrum of MWCNT-OH, indicating the presence of hydroxyl and carboxyl groups on the surface of the MWCNT [Fig. S5]. Quantitative XPS analysis indicated circa 3.96 at% of oxygen was present in MWCNT-OH [Fig. S6].

In the next step, three different hybrid materials were synthesised [Table 1, Fig. S3]. For the first material, denoted as CTF1@MWCNT-OH, terephthalonitrile was applied as the monomer which contained no additional nitrogen other than the nitrogen present in the triazine rings. The two other hybrid materials, pyCTF@MWCNT-OH and HATCTF@MWCNT-OH,

were built from 2,6-pyridinedicarbonitrile and HAT respectively [Fig. 1]. These monomers both contain pyridinic nitrogen. Although this is still under debate, several authors have claimed that the pyridinic nitrogens are the most active sites for CO₂ reduction in nitrogen-doped carbons^{16,31}. These hybrid materials were synthesized using the ionothermal method, in which the terminal nitrile groups from three monomers fuse together in a cyclotrimerization reaction to form a triazine ring [Fig. S3]. This trimerization reaction relies on the use of high temperatures (400°C or 500°C) depending on the choice of the monomer, in the presence of MWCNT-OH and ZnCl₂. For comparison, the bulk HATCTF, pyCTF and CTF1 were also prepared under identical reaction conditions, but in the absence of the MWCNT-OH.

Table 2 – elemental analysis and N₂-sorption results

Name	A _{BET} (m ² /g)	V _m (cm ³ /g)	N (wt%)	C (wt%)	H (wt%)
MWCNT-OH	263	1.58	0.33	91.92	0.14
CTF1@MWCNT-OH	323	0.34	3.33	87.52	0.70
pyCTF@MWCNT-OH	496	0.41	6.57	77.47	0.66
HATCTF@MWCNT-OH	290	0.76	8.27	81.74	0.67

Elemental analysis indicated a significant increase in the nitrogen content of the hybrid materials in comparison to the pristine MWCNT-OH material which exhibited only 0.33 wt% of nitrogen [Table 2]. The highest nitrogen content was observed for the HATCTF@MWCNT-OH material (8.27 wt%), followed by the pyCTF@MWCNT-OH (6.57 wt%) and the CTF1@MWCNT-OH which has a nitrogen content of 3.33 wt%.

In Fig. 3a a comparison of the PXRD patterns of the MWCNT-OH, HATCTF and HATCTF@MWCNT-OH is depicted. For all the CTF based materials a broad (001) diffraction around 2θ = 26° is observed which can be attributed to a vertical spacing between the stacked sheets of 3.35 Å³². A diffraction at a similar angle is seen in the pristine MWCNT-OH material, which corresponds to the (002) diffraction coming from the interlayer distance between the different concentric single-walled carbon nanotubes that make up a multiwalled carbon nanotube³³. In addition to this, the MWCNT-OH shows another diffraction at approximately 43°, which can be assigned to the (100) and (101) diffractions in the coiled carbon sheets of carbon

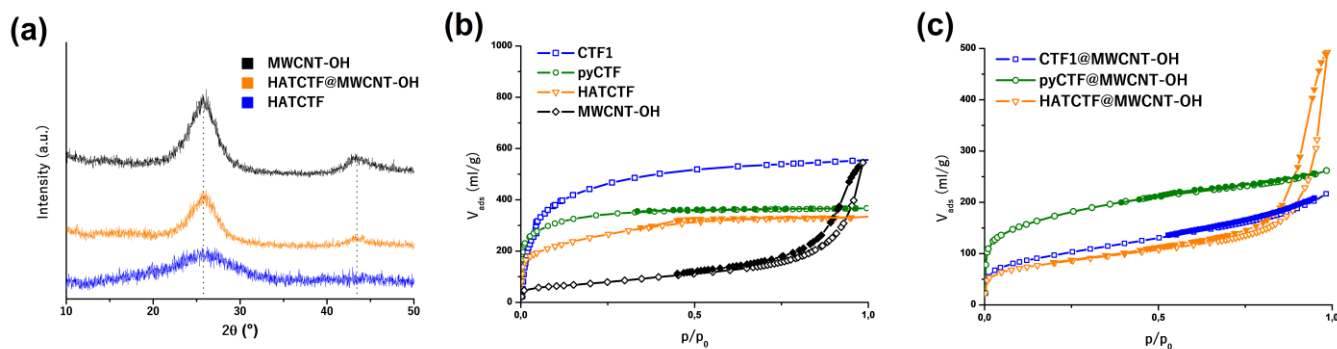


Figure 3: (a) PXRD patterns of MWCNT-OH, HATCTF and HATCTF@MWCNT-OH (b) N₂-physisorption of the MWCNT, CTF1, pyCTF, HATCTF (c) N₂-physisorption of the respective hybrid materials

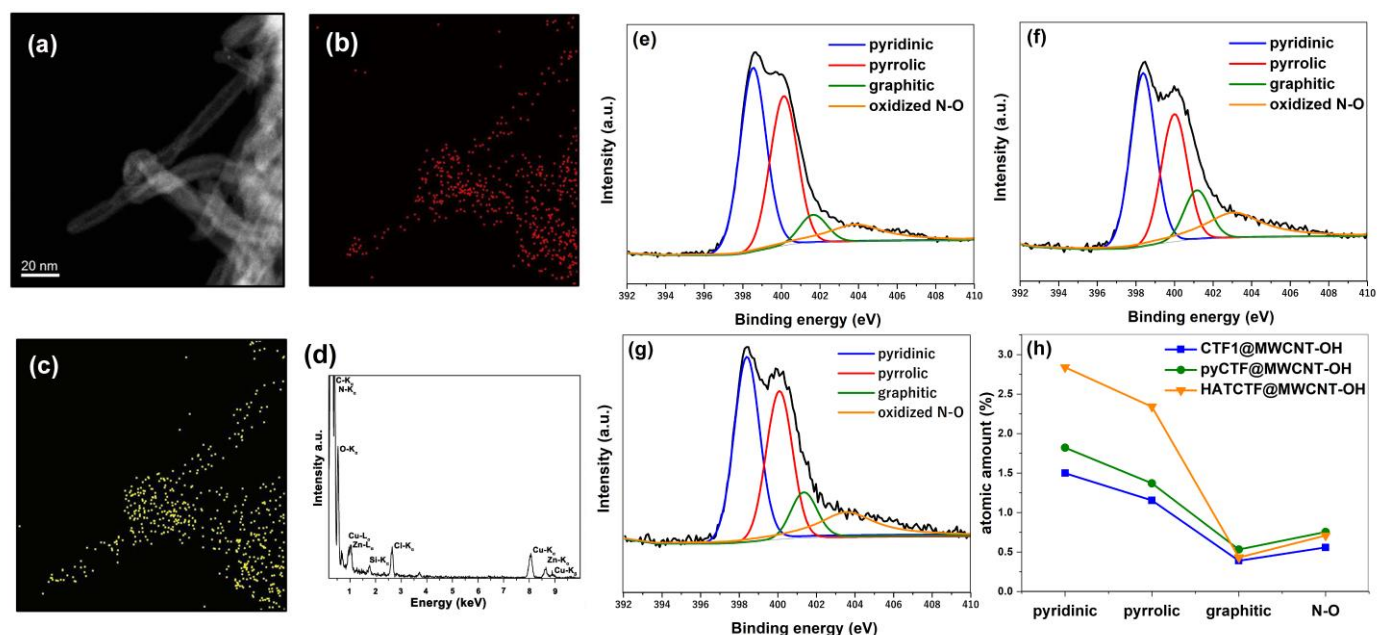


Figure 4: (a) ADF-STEM image of nanotubes in the HATCTF@MWCNT-OH material showing the mapped area together with EDX elemental maps for (b) oxygen, (c) nitrogen and (d) corresponding EDX spectrum with a clear nitrogen signal. (e) Deconvoluted XPS spectrum of the N1s peak of HATCTF@MWCNT-OH, (f) deconvoluted XPS spectrum of the N1s peak of pyCTF@MWCNT-OH, (g) deconvoluted XPS spectrum of the N1s peak of CTF1@MWCNT-OH, (h) atomic nitrogen distribution of HATCTF@MWCNT-OH, pyCTF@MWCNT-OH and CTF1@MWCNT-OH

nanotubes^{33,34}. This diffraction is not observed in the bulk HATCTF material, but is clearly present in the hybrid material HATCTF@MWCNT-OH. The PXRD patterns of CTF1, pyCTF, CTF1@MWCNT-OH and pyCTF@MWCNT-OH can be found in Fig. S7.

Further elucidation on the formation of the hybrid materials was found by means of N₂-physisorption measurements [Fig. 3b,c]. The bulk CTF materials exhibit a type I isotherm, typical for a microporous material. The functionalized carbon nanotubes on the other hand exhibit a type IV isotherm: in between the randomly entangled carbon nanotubes are voids, where capillary condensation can take place at a P/P₀ values close to 1. The isotherm of the HATCTF@MWCNT-OH exhibits both microporosity and capillary condensation, but to a lesser extent than what is observed in the MWCNT-OH material. We postulate that the voids between the carbon nanotubes are filled with CTF. For the pyCTF-MWCNT-OH and CTF1-MWCNT-OH material, capillary condensation is no longer observed at all. A possible explanation lies in the significant difference of the monomers: 128 g/mol and 129 g/mol for terephthalonitrile and 2,6-pyridinedicarbonitrile respectively, versus 399 g/mol for hexaazatriphenylenetrimethoxytrinitrile. Because for all materials an equal weight ratio of 1:2 monomer to MWCNT-OH was used, the pyCTF@MWCNT-OH and CTF1@MWCNT-OH reaction mixtures contain a larger volume of CTF as compared to HATCTF@MWCNT-OH, enough to entirely fill the voids between the multiwalled carbon nanotubes. The molar amount of hexaazatriphenylenetrimethoxytrinitrile is not sufficient to entirely fill the mesoporous voids between the carbon nanotubes with HATCTF. This theory is supported by the changes in the BET surface area and total pore volume for the hybrid materials as

compared to MWCNT-OH [Table 2]. For HATCTF@MWCNT-OH, the decrease in total pore volume is less pronounced than for pyCTF@MWCNT-OH and CTF1@MWCNT-OH. On the other hand, the increase in surface area for the hybrid materials is smaller for HATCTF@MWCNT-OH in comparison to the other hybrid materials. The filling of the mesoporous carbon nanotubes voids by the CTF causes the overall pore volume to decrease, but the BET surface area to increase, with both effects being more pronounced as a higher amount of CTF is present.

A combination of ADF-STEM imaging with EDX elemental mapping was exploited to investigate the morphology and chemical composition of the MWCNT-OH and the hybrid materials. Fig. S8 contains the ADF-STEM overview and elemental maps for the MWCNT-OH material as well as the EDX spectrum and a HR ADF-STEM image of the multiwalled nanotubes functionalised with -OH groups. A clear oxygen signal is detected for the material and the oxygen distribution nicely correlates to the carbon distribution evidencing the -OH functionalisation of the carbon nanotubes which is in good agreement with the FTIR measurement results. The MWCNT-OH retained the classical multiwalled morphology [Fig. S8e]. Further on, the hybrid materials were subjected to an investigation at the same conditions. Fig. S9 contains an ADF-STEM overview and the elemental maps for the HATCTF@MWCNT material. A higher agglomeration of the nanotubes is typical for the HATCTF-functionalised material in comparison to the -OH-functionalised nanotubes. Most probably this effect is related to the ability of the HATCTF to fill in the space between the nanotubes. Fig. 4a depicts an ADF-STEM image of the HATCTF-functionalised multiwalled nanotubes, while Fig. 4b,c show the correlating presence of respectively oxygen and nitrogen in HATCTF@MWCNT-OH, indicating the growth of nitrogen-rich

HATCTF onto the carbon nanotube surface via oxygen linkages. A clear nitrogen signal in the EDX spectrum taken from a few nanotubes shown in Fig. 4a is detected [Fig. 4d]. It is evidencing the nitrogen presence in and around the nanotubes of HATCTF@MWCNT rather than a separate nitrogen-containing phase intermixing into agglomerates with nanotubes. No secondary phases were observed also indicating the decoration of the MWCNT-OH by the HATCTF and creation of the hybrid material. In Fig. S10, the ADF-STEM image showing the mapped area together with elemental maps, EDX spectrum and HR ADF-STEM image of a single nanotube for the pyCTF@MWCNT-OH material are depicted. The EDX spectrum contains clear peaks of both nitrogen and carbon, while the morphology of a single nanotube [Fig. S10f] still stays regular. The distribution of oxygen and nitrogen signals [Fig. S10b,c,d] come in agreement revealing the functionalisation of the multiwalled nanotubes.

XPS analysis of the hybrid materials indicated the presence of four distinct types of nitrogen: pyridinic-like nitrogen, pyrrolic-like nitrogen, graphitic nitrogen and oxygenated N-O species [Fig. 4e,f,g]. Despite the different monomer, the nitrogen distribution of pyCTF@MWCNT-OH and CTF1@MWCNT-OH show a very similar trend [Fig. 4h]. The HATCTF@MWCNT-OH on the other hand is significantly richer in pyridinic and pyrrolic nitrogen, most likely as a result of the monomer, which is rich in pyridinic nitrogen.

Evaluation of the electrocatalytic performance of the CTF@MWCNT based materials

Each hybrid material was coated onto a glassy carbon electrode with a loading of $\sim 1 \text{ mg/cm}^2$. The activity in the CO_2 reduction of the hybrid materials was examined by 200 second chronoamperometry tests at different potentials in a range of -0.5 V to -0.9 V vs. RHE. At every potential an increase in current density was observed for HATCTF@MWCNT-OH in CO_2 -saturated 0.1 M KHCO_3 as compared to the same electrolyte sparged with argon, indicating the occurrence of electrochemical CO_2 reduction [Fig. 5a]. Online GC analysis of the cell headspace during 1800 second chronoamperometry experiments confirmed this statement. CO and H_2 could be detected during the reaction in the CO_2 -saturated 0.1 M KHCO_3 electrolyte at potentials as high as -0.5 V (versus RHE). The FE for CO in the range of -0.5 V to -0.9 V (versus RHE) for all materials is shown in Fig. 5b and is maximal at the highest tested WE potential of -0.5 V. The rate of the competing hydrogen evolution reaction increases with decreasing WE potential. For all the hybrid materials, the FE for CO generation was maximal at -0.5 V, corresponding to an overpotential of circa 380 mV⁴. A clear correlation between the nitrogen content and the maximal FE at -0.5 V can be noted: while the nitrogen-poor CTF1@MWCNT-OH only produces 41% CO , pyCTF@MWCNT-OH and HATCTF@MWCNT-OH (containing 6.57 wt% and 8.27 wt% nitrogen respectively) generate 60% and 81% CO respectively. Upon shifting to more negative potentials, the CO generation decreased, while at the same time more H_2 was detected by the GC, meaning that lower potentials will foster hydrogen evolution at the cost of CO_2 reduction. The shift from CO to H_2 production happens almost linearly with increasingly

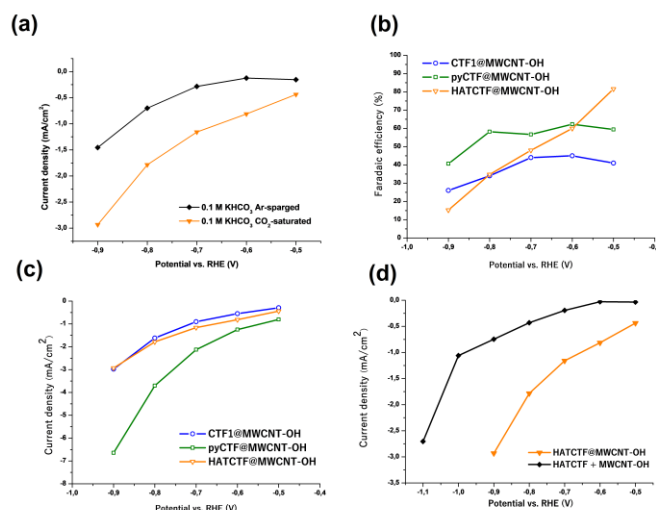


Figure 5: (a) geometric current density of HATCTF@MWCNT-OH in Ar-sparged 0.1 M KHCO_3 and CO_2 -saturated 0.1 M KHCO_3 ; (b) FEs for CO of the hybrid materials; (c) total geometric current densities of the hybrid materials; (d) geometric current density for HATCTF@MWCNT-OH compared to HATCTF+MWCNT-OH

negative potential in HATCTF@MWCNT-OH. In CTF1@MWCNT-OH and pyCTF@MWCNT-OH, however, the FE for CO decreases less steep. These results can be explained by the observations made by N_2 -sorption: HATCTF@MWCNT-OH contains a lower molar ratio of CTF to carbon nanotubes as compared to pyCTF@MWCNT-OH and CTF1@MWCNT-OH. As carbon nanotubes are known to catalyze hydrogen evolution³⁵, the relatively larger amount of it present in HATCTF@MWCNT-OH will more effectively promote hydrogen evolution at lower potentials. Interestingly, the current densities of HATCTF@MWCNT-OH and CTF@MWCNT-OH are very similar while pyCTF@MWCNT-OH shows more electrochemical activity at every potential [Fig. 5c]. This trend does not agree with the nitrogen content as detected by XPS or elemental analysis, but does correlate with the BET surface area: where HATCTF@MWCNT-OH and CTF1@MWCNT-OH show a comparable specific surface area around $300 \text{ m}^2/\text{g}$, the increased specific surface area (almost $500 \text{ m}^2/\text{g}$) of pyCTF@MWCNT-OH might explain the enhanced activity of this catalyst. [Table 2].

In order to prove the importance of the chemical bonding between the CTF and the carbon nanotube, a blank electrocatalytic test was performed in which a physical mixture of HATCTF and MWCNT-OH was used. More specifically, HATCTF and MWCNT-OH were mixed together in a mortar in a 1:2 weight ratio, denoted as HATCTF+MWCNT-OH. While this sample also contains CTF and MWCNT-OH in the same weight ratio, they are not fused together, as is the case for HATCTF@MWCNT-OH [Fig. S11]. The CO current density at -0.5 V of the former sample was decreased by more than a factor 10 as compared to the HATCTF@MWCNT-OH [Fig. 5d].

Conclusions

An in situ growth strategy successfully yielded hybrid materials, composed of a layer of CTF grown on multiwalled carbon nanotubes via oxygen linkages. The hybrid materials

were capable of selective electrochemical conversion of CO₂ to CO. The best results were obtained with HATCTF@MWCNT-OH, achieving 81 % FE at the very low overpotential of 380 mV and with a total current density of -0.48 mA/cm². At this overpotential, the HATCTF@MWCNT-OH shows at least a tenfold increase in CO generation activity as compared to a physical mixture of the HATCTF and MWCNT-OH. This observation indicates that the reported novel hybridization method is indeed a viable strategy to use the poorly conductive CTFs as part of a functional electrocatalyst, whilst retaining their structural and chemical properties. XPS analysis indicated that the bottom-up synthesis strategy of CTFs offers some degree of control over the nature of the active sites via adequate choice of monomer. The harsh ionothermal synthesis method however still causes unwanted side-reactions, leading to a range of nitrogen species in the material. The authors of this article will conduct research in the near future towards the use of a mild method for the synthesis of well-defined CTF@MWCNT-OH materials for applications in electrocatalysis.

Conflicts of interest

The authors declare no conflicts of interest.

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Notes and references

- 1 C. Le Quéré, R. M. Andrew, P. Friedlingstein, S. Sitch, J. Hauck, J. Pongratz, P. A. Pickers, J. I. Korsbakken, G. P. Peters and J. G. Canadell, *Earth Syst. Sci. Data*, 2013, **42**, 2423–2436.
- 2 C. Chen, J. F. K. Kotyk and S. W. Sheehan, *Chem.*
- 3 C. Costentin, M. Robert and J. M. Saveant, *Chem. Soc. Rev.*, 2013, **42**, 2423–2436.
- 4 W. Zhang, Y. Hu, L. Ma, G. Zhu, Y. Wang, X. Xue, R. Chen, S. Yang and Z. Jin, *Adv. Sci.*
- 5 P. P. Sharma and X. D. Zhou, *Wiley Interdiscip. Rev. Energy Environ.*
- 6 M. Jouny, W. Luc and F. Jiao, *Ind. Eng. Chem. Res.*, 2018, **57**, 2165–2177.
- 7 J. M. Spurgeon and B. Kumar, *Energy Environ. Sci.*, 2018, **11**, 1536–1551.
- 8 S. Verma, B. Kim, H. R. M. Jhong, S. Ma and P. J. A. Kenis, *ChemSusChem*, 2016, **9**, 1972–1979.
- 9 X. Duan, J. Xu, Z. Wei, J. Ma, S. Guo, S. Wang, H. Liu and S. Dou, *Adv. Mater.*, 2017, **29**, 1–20.
- 10 P. Veerakumar, P. Thanasekaran, T. Subburaj and K.-C. Lin, *C*, 2018, **4**, 54.
- 11 J. Wu, S. Ma, J. Sun, J. I. Gold, C. Tiwary, B. Kim, L. Zhu, N. Chopra, J. Lou, G. Ding, P. J. A. Kenis and P. M. Ajayan, *Nat. Commun.*, 2016, **7**, 1–6.
- 12 Z. Chen, K. Mou, S. Yao and L. Liu, *J. Mater. Chem. A*, 2018, **6**, 11236–11243.
- 13 H. Yang, Y. Wu, Q. Lin, L. Fan, X. Chai, Q. Zhang, J. Liu, C. He and Z. Lin, *Angew. Chemie - Int. Ed.*, 2018, **57**, 15476–15480.
- 14 Y. Liu, S. Chen, X. Quan and H. Yu, *J. Am. Chem. Soc.*, 2015, **137**, 11631–11636.
- 15 B. Kumar, M. Asadi, D. Pisasale, S. Sinha-Ray, B. A. Rosen, R. Haasch, J. Abiade, A. L. Yarin and A. Salehi-Khojin, *Nat. Commun.*, 2013, **4**, 1–8.
- 16 H. Wang, J. Jia, P. F. Song, Q. Wang, D. B. Li, S. X. Min, C. X. Qian, L. Wang, Y. F. Li, C. Ma, T. Wu, J. Y. Yuan, M. Antonietti and G. A. Ozin, *Angew. Chemie-International Ed.*, 2017, **56**, 7847–7852.
- 17 C. S. Diercks and O. M. Yaghi, *Science (80-)*.
- 18 L. J. Yang, S. J. Jiang, Y. Zhao, L. Zhu, S. Chen, X. Z. Wang, Q. Wu, J. Ma, Y. W. Ma and Z. Hu, *Angew. Chemie-International Ed.*, 2011, **50**, 7132–7135.
- 19 J. Xie, X. Zhao, M. Wu, Q. Li, Y. Wang and J. Yao, *Angew. Chemie - Int. Ed.*, 2018, **57**, 9640–9644.
- 20 P. Kuhn, M. Antonietti and A. Thomas, *Angew. Chemie-International Ed.*, 2008, **47**, 3450–3453.
- 21 D. Y. Osadchii, A. I. Olivos-Suarez, A. V. Bavykina and J. Gascon, *Langmuir*, 2017, **33**, 14278–14285.
- 22 P. Su, K. Iwase, T. Harada, K. Kamiya and S. Nakanishi, *Chem. Sci.*, 2018, **9**, 3941–3947.
- 23 C. Lu, J. Yang, S. Wei, S. Bi, Y. Xia, M. Chen, Y. Hou, M. Qiu, C. Yuan, Y. Su, F. Zhang, H. Liang and X. Zhuang, *Adv. Funct. Mater.*, 2019, **29**, 1–8.
- 24 X. Zhu, C. Tian, H. Wu, Y. He, L. He, H. Wang, X. Zhuang, H. Liu, C. Xia and S. Dai, *ACS Appl. Mater. Interfaces*, 2018, **10**, 43588–43594.
- 25 Y. Wang, J. Chen, G. Wang, Y. Li and Z. Wen, *Angew. Chemie*, 2018, **130**, 13304–13308.
- 26 K. Kanakarajan and A. W. Czarnik, *J. Org. Chem.*, 1986, **51**, 5241–5243.
- 27 J. T. Rademacher, K. Kanakarajan and A. W. Czarnik, *Synthesis (Stuttg.)*, 1994, **1994**, 378–380.
- 28 T. H. Chang, B. R. Wu, M. Y. Chiang, S. C. Liao, C. W. Ong, H. F. Hsu and S. Y. Lin, *Org. Lett.*, 2005, **7**, 4075–4078.
- 29 A. Kovács, R. Schierholz and K. Tillmann, *J. large-scale Res. Facil. JLSRF*, 2016, **2**, 43.
- 30 M. Masteri-Farahani and S. Abednatanzi, *J. Sci. Islam. Repub. Iran*, 2014, **25**, 27–33.
- 31 S. Zhang, P. Kang, S. Ubnoske, M. K. Brennaman, N. Song, R. L. House, J. T. Glass and T. J. Meyer, *J. Am. Chem. Soc.*, 2014, **136**, 7845–7848.
- 32 P. Katekomol, J. Roeser, M. Bojdys, J. Weber and A. Thomas, *Chem. Mater.*, 2013, **25**, 1542–1548.
- 33 Y. Saito, T. Yoshikawa, S. Bandow, M. Tomita and T. Hayashi, *Phys. Rev. B*, 1993, **48**, 1907.
- 34 Vinod Gupta and Tawfik A. Saleh, *Carbon Nanotub. - From*

- 35 *Res. to Appl.*, 2011, 295–312.
- W. Cui, Q. Liu, N. Cheng, A. M. Asiri and X. Sun, *Chem. Commun.*, 2014, **50**, 9340–9342.