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Additional Information

Cobalt Metal Organic Framework based on Layered Double Nanosheets for Enhanced Electrocatalytic Water Oxidation in Neutral Media

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Abstract

A new cobalt metal-organic framework (**2D-Co-MOF**) based on well-defined layered double cores that are strongly connected by intermolecular bonds has been developed. Its 3D structure is held together by π - π stacking interactions between the labile pyridine ligands of the nanosheets. In aqueous solution, the axial pyridine ligands are exchanged by water molecules producing a delamination of the material, where the individual double nanosheets preserve their structure. The original 3D layered structure can be restored by a solvothermal process with pyridine, so that the material shows “memory effect” during delamination-pillarization process. Electrochemical activation of a **2D-Co-MOF**@Nafion-modified graphite electrode in aqueous solution improves the ionic migration and electron transfer across the film, and promotes the formation of the electrocatalytically active cobalt species for the oxygen evolution reaction (OER). The so-activated **2D-Co-MOF**@Nafion composite exhibits an outstanding electrocatalytic performance for the OER at neutral pH, with a TOF value (0.034 s^{-1} at overpotential of 400 mV) and robustness superior to those reported for similar electrocatalysts under similar conditions.

The particular topology of the delaminated nanosheets, with quite distant cobalt centers, precludes the direct coupling between the electrocatalytically active centers of the same sheet. On the other hand, the increase of ionic migration across the film during the electrochemical activation stage rules out the inter-sheets coupling between active cobalt centers as this scenario would impair electrolyte permeation. Altogether, the most plausible mechanism for the O–O bond formation is the water nucleophilic attack to single Co(IV)-oxo or Co(III)-oxyl centers. Its high electrochemical efficiency suggests that the presence of nitrogen-containing aromatic equatorial ligands facilitates the water nucleophilic attack as in the case of the highly efficient cobalt porphyrins.

Introduction

Water splitting is one of the most important processes for many applications associated with carbon-free energy storage and conversion.¹⁻³ Water oxidation (WO) or oxygen evolution reaction (OER) is a more complex transformation than proton reduction, and for this reason it is still considered the most challenging step in water splitting.⁴⁻⁵ In fact, OER is crucial to produce oxygen from water successfully,⁶⁻⁷ as well as for other applications such as regenerating fuel cells⁸ and rechargeable metal-air batteries.⁹

Precious metal oxides IrO₂ and RuO₂ are, so far, the most efficient OER electrocatalysts but their high cost, scarcity and low durability make them impractical for large-scale applications.¹⁰⁻¹¹ Other OER catalysts (mostly metal oxides/hydroxides)¹² generally show unsatisfactory catalytic activities with large overpotentials.^{10-11,13-15} Cobalt-based water oxidation electrocatalysts (WOC), including molecular complexes^{5,16-17} and inorganic nanoparticles,¹⁸⁻²² are of great interest due to their notable OER activities and abundance of this metal in the earth.^{3,23-25} MOFs are a novel class of porous materials that are emerging in the research of electrochemical water splitting due to their large surface areas, controllable arrangement of isolated active sites, and high design flexibility.²⁶⁻²⁷ However, few works report on the construction of cobalt based MOF for electrocatalytic OER,²⁸⁻⁴¹ despite their large structural features. This type of materials has typically suffered from low conductivity and low electrocatalytic activity, so a large number of research efforts have been made to overcome these limitations. Strategies reported to facilitate the charge transport across the MOF include the increase of the charge delocalization by introducing donor-acceptor type interactions,⁴²⁻⁴⁵ mixed valent states of the node/linker,⁴⁶⁻⁴⁷ and π - π stacking or π -conjugation into the framework.⁴⁸ Besides, effective strategies to enhance the intrinsic electrocatalytic activity of MOF are focused on the increase of the accessibility of the active sites³⁶⁻³⁸ and modulation of their electronic environment.^{35,39-41,49} The optimization of coordinative unsaturated metal sites of MOFs has been achieved by tuning the synthetic protocol^{38,49-50} and/or post-treatment methods via MOF activation by solvent-assisted ligand exchange,⁴⁹ plasma engraving^{36,51} or electrochemical activation.^{32,38-40} Furthermore, electronic structures of the

building units of MOFs have been modulated by incorporating missing linker and missing node defect^{37,49,52-54} or by construction of hybrid MOF heterostructures containing two or more different kinds of metal ions or organic linkers.^{34-35,39-41} Because of its intrinsic high kinetic barrier, most of the reported cobalt-based MOF electrocatalysts for OER operate at strongly alkaline media, which implies very highly corrosive and harsh conditions for large-scale applications. Hence, a major challenge is the development of new MOFs for efficient electrocatalytic water oxidation at neutral pH.

Besides, previous studies have shown that the electrocatalytic active species for the cobalt-mediated OER are the Co(IV)-oxo or Co(III)-oxyl radical species generated from the resting state of the cobalt centers by proton-coupled electron transfers. In this sense, different mechanisms have been proposed for the cobalt-mediated O-O bond formation, namely: *i*) direct coupling between two oxo or oxyl ligands located in distinct cobalt centers, that produces a bridging peroxo intermediate,^{55,56} *ii*) geminal coupling of an oxo (or oxyl) ligand with another water-derived ligand coordinating the same cobalt center^{57,58} or *iii*) water nucleophilic attack to the oxo or oxyl radical ligands generating the corresponding hydroperoxide intermediate.⁵⁹⁻⁶¹ Unfortunately, despite previous efforts the exact mechanism is still unresolved.

Herein, a new cobalt MOF based on well-defined layered double cores (**2D-Co-MOF**) has been synthesized. These layered double cores are strongly connected by intermolecular bonds, holding its 3D structure together by π - π stacking interactions between the labile pyridine ligands of the nanosheets. Treatment of this π -stacked **2D-Co-MOF** with water provokes the exchange of the axial labile pyridine ligands by water molecules that triggers the delamination of the material producing double nanosheets (delaminated **2D-Co-MOF**), which opens up the formation of active cobalt sites for its application in the OER. In addition, its dispersion in Nafion provides a composite (**2D-Co-MOF@Nafion**) with a good adherence to graphite electrodes suitable for the electrocatalytic water oxidation reaction. Moreover, electrochemical activation of the composite facilitates both ionic migration and electron transfer across the film, which in turn generates more open active cobalt sites for water oxidation. The fully activated **2D-Co-**

MOF@Nafion composite exhibits superior electrocatalytic performance for OER at neutral pHs than similar nanosheet-based materials reported in literature. This enhanced electrocatalytic activity can be ascribed to the presence of nitrogen-containing aromatic equatorial ligands that promotes the water nucleophilic attack as in the case of the highly efficient cobalt porphyrins and related systems commonly employed as catalysts for the homogeneous water oxidation reaction.^{62,63}

Discussion and Results

Synthesis and Characterization of π - π Stacked **2D-Co-MOF**

The new **2D-Co-MOF** was obtained by solvothermal synthesis at 150°C for 9 days. The cubane cobalt cluster $[\text{Co}_4\text{O}_4(\text{OAc})_4(\text{Py})_4]^{64}$ has been seen to be a key for the synthesis of the new **2D-Co-MOF** material since other common reagents such as $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ or $\text{Co}(\text{OAc})_2$ were unsuccessful to obtain this new material in a wide range of different synthetic conditions (Figure S1, Table S1). The solvothermal reaction of $[\text{Co}_4\text{O}_4(\text{OAc})_4(\text{py})_4]$ and 2,2'-bipyridine-4,4'-dicarboxylic acid (H_2bda) in pyridine results in the formation of red crystals of **2D-Co-MOF**. Single crystal X-ray diffraction reveals that **2D-Co-MOF** crystallizes in the monoclinic $P2_1/n$ space group (Figure S2 and Table S2). The Co^{2+} atom lies in a distorted octahedral environment (Figure 1a and S3) and is coordinated by three oxygen atoms from three different bda^{2-} ligands, one of them in an axial position (oxygen sp^2 of carboxylic group) and the other two which take up two of the equatorial positions (alkoxy substituent of carboxylic group). These carboxylate groups are chelating monodentate and each oxygen of a carboxylic group is coordinated with a different cobalt center. Each Co^{2+} ion is also bidentately coordinated to two nitrogen atoms of one bda^{2-} ligand, different from the three which are coordinated to the cobalt by the carboxylic group, and to a nitrogen atom from a pyridine ligand, which occupies the second axial position to form six-coordinate metal ions (Figures S4 and S5).

This material extends in two directions of the space forming a 3D layer material consisting of nanosheets comprised of two single layers with an interplanar distance of 3.491 Å (Figure 1b and S6). Consecutive nanosheets are further packed into three-dimensional supramolecular structures through interlayer face-to-face $\pi \cdots \pi$ interactions between pyridine ligands (Figure 1c and S7). The distance between the centroids of the pyridine rings is 4.238 Å. Two cobalt atoms of two different layers are connected by two carboxylate groups of two different bda²⁻ ligands, being the distance between these two cobalt ions 4.69 Å.

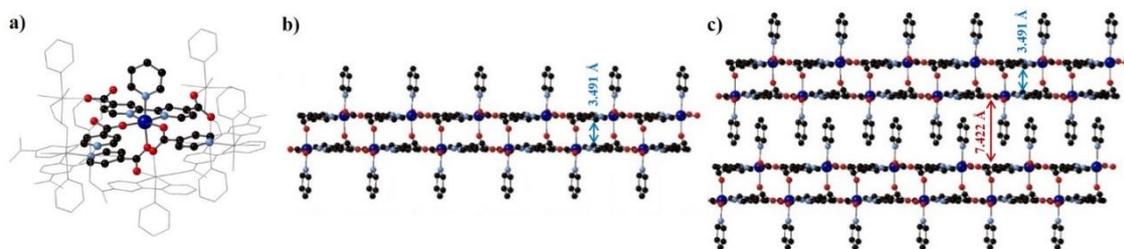


Figure 1. X-ray structure of a) the secondary building unit, b) a layered double nanosheet and c) a π - π stacked two layered double nanosheets of **2D-Co-MOF**. The blue arrow indicates the distance between the two single layers of a nanosheet (3.491 Å), and the red arrow indicates the inter-sheet distance between π - π stacked nanosheets (7.422 Å).

The chemical analysis of this new material was determined by Elemental Analysis (EA) and Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES). The obtained results (C: 55.07%; H: 3.05%; N: 10.77%; Co: 15.05%) match well with the formula $C_{18}H_{11}CoN_3O_4$ determined by single crystal X-ray diffraction (more information in SI). Thermal stability was tested by thermogravimetric analysis (Figure S8), which is characterized by three mass loss steps. The first one at 120 °C is ascribed to the solvent enclosed in the material, whereas the other two overlapped steps around 400 °C correspond to the loss of pyridine and bda ligands (more details in SI). The microporosity of the material has been demonstrated upon activation at 100 °C under vacuum, with a moderate CO_2 adsorption capacity of 1.1 mmol/g at 0°C and 100 kPa (Figure S9a-b), which corresponds to an apparent surface area of 61m²/g.

In order to provide further composition characterization, **2D-Co-MOF** was studied by FESEM (Field Emission Scanning Electron Microscopy) and EDX (Energy Dispersive X-ray spectroscopy) analysis (Figure 2a). **2D-Co-MOF** crystals have a hexagonal morphology and all its elements are well distributed as can be observed in the EDX images.

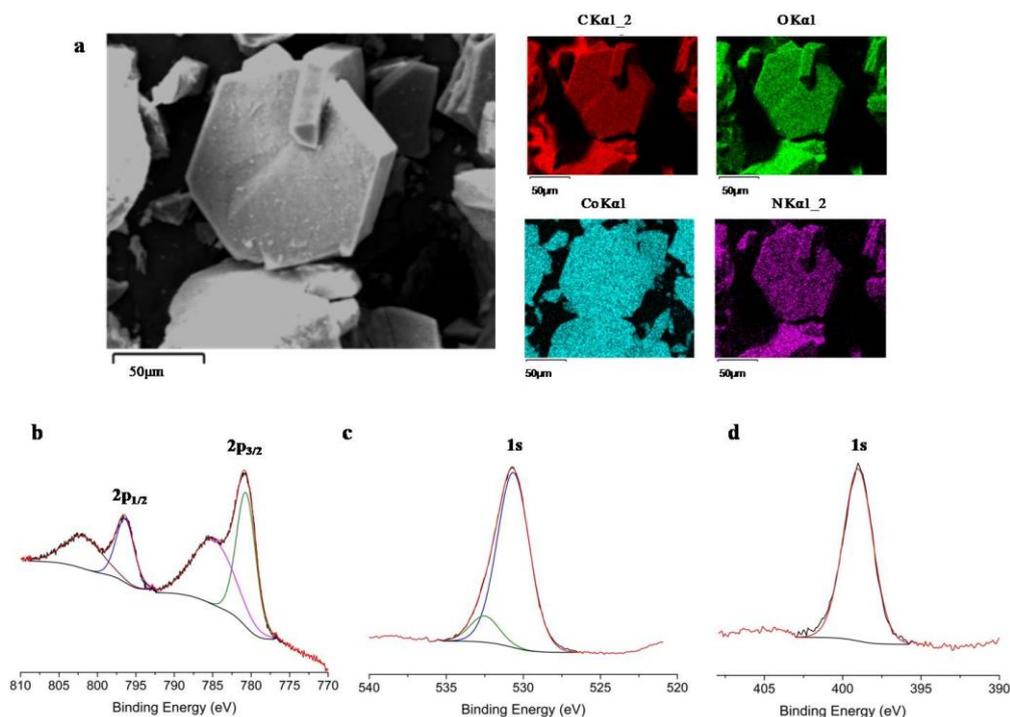


Figure 2. a) FESEM image of **2D-Co-MOF** and its EDX analysis. Bottom panel: XPS spectra of b) Co 2p line c) O 1s line and d) N 1s line of **2D-Co-MOF**.

The electronic structure of this material was also analyzed by X-ray photoelectron spectroscopy (XPS) (Figure 2b-d) to elucidate the nature of the coordination environment. The survey spectrum shows the presence of cobalt, oxygen, carbon and nitrogen. The analysis of XPS spectra of 2p transition metals is not a straightforward process as they contain multiplet splitting and shake-up structures that may prove difficult in the identification of the chemical states present.⁶⁵ The binding energy (E_b) value is typically used in XPS to determine the oxidation number of a chemical element, though for the 3d transition elements the spin-orbit splitting is more informative. According to theoretical calculations,⁶⁶ the Co 2p_{1/2}-Co 2p_{3/2} spin-orbit splitting increases when increasing the number of the unpaired 3d-electrons, being closer to 16 eV for high spin Co (II) and to 15 eV for Co (III). For the current **2D-Co-MOF**, E_b (Co 2p_{3/2}), E_b (Co 2p_{1/2})

and ΔE_1 values are 780.7, 796.4 and 15.7 eV, respectively (Figure 2b). Intense satellite peaks ($\Sigma\text{sat}/\text{ICo}_{2p} > 1.6$) have been observed for the Co 2p_{3/2} spectra. Both $\Sigma\text{sat}/\text{ICo}_{2p}$ and ΔE_1 values are characteristic of the high-spin cobalt(II) compounds,⁶⁷⁻⁷⁰ indicating that the cobalt centers of **2D-Co-MOF** are exclusively in the Co(II) oxidation state. In addition, the O 1s peak was deconvoluted into two components at 531.1 and 532.6 eV corresponding to O=C-O and C-O, respectively (Figure 2c). Finally, the N 1s peak presents only one contribution at 399 eV characteristic of pyridinic nitrogen (Figure 2d).

Finally, the chemical stability of the new **2D-Co-MOF** material in different solvents was investigated from the powder diffraction patterns measured after contacting this material with protic solvents such as ethanol and water, non-protic solvents such as acetonitrile, and strongly alkaline solvent such as triethylamine (pH = 12.7) (Figures S10 and S11). The X-ray powder diffraction spectra reveal that this material maintains its structure intact after being treated with ethanol, acetonitrile and triethylamine at 25°C during 1 day. However, treatment with water produces significant structural changes as described in the next section.

Reversible Chemical Delamination of the π - π Stacked 2D-Co-MOF

In order to assess the chemical stability of the so-developed cobalt MOF in water for its application to promote the oxygen evolution reaction, further experiments have been carried out to probe their structural implications. In particular, Raman, PXRD and XPS spectra of the π -stacked **2D-Co-MOF** have been measured before and after its treatment with water for 5 minutes. As can be seen in the Raman spectra depicted in Figure 3, the most striking findings in the presence of water (red spectrum) is the loss of the Raman bands associated with the axially coordinated pyridine ligands (768, 1010 and 1283 cm⁻¹), and the insensitivity of the bands associated with the bipyridine (774, 1022 and 1278 cm⁻¹) and the carboxylic groups (1289, 1426, 1546 and 1615 cm⁻¹), indicating that the cobalt centers preserve their coordination to the bda and carboxylic ligands after treatment with water. Interestingly, the XPS spectrum of the **2D-Co-MOF** after treatment with water reveals the presence of a shoulder at 532.8 eV in the main O1s peak, which is ascribed to cobalt-coordinated water molecules,⁷¹ thereby suggesting

that the axial labile pyridine ligand is replaced by water molecules (Figure S12). Additionally, the overall change of the PXRD pattern, with the loss or broadening of some characteristic bands (red spectrum in Figure 3), is consistent with a delamination of the π -stacked 3D structure of the MOF to produce individual nanosheets, whose double layer structure is preserved.

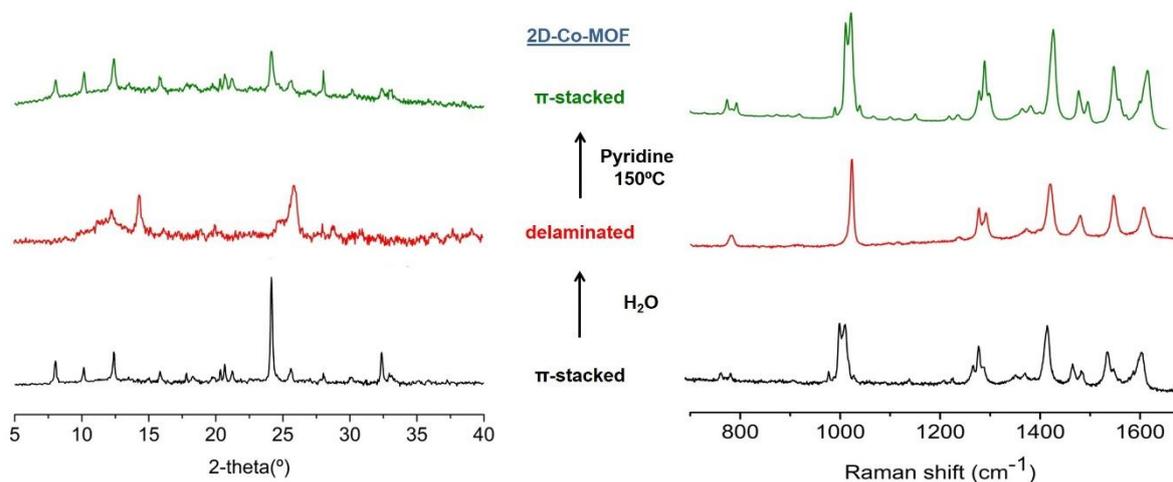


Figure 3. Power x-ray diffraction patterns (left panel) and Raman spectra (right panel) of π -stacked **2D-Co-MOF** before (black) and after successive treatment with H₂O for 5 minutes (red) and pyridine for 2 days at 150 °C (green). Note: PXRD of delaminated and regenerated π -stacked Co-MOF have been acquired in a zero background holder.

Interestingly, we have found that the 3D structure of the delaminated **2D-Co-MOF** can be regenerated by solvothermal process with pyridine at 150 °C for 2 days (green spectra in Figure 3). This fact has been corroborated using XPS, where the shoulder at 532.8 eV in the main O1s peak, which is ascribed to cobalt-coordinated water molecules, disappears after the solvothermal treatment with pyridine (Figure S14), indicating the coordination of the pyridines in the axial position again and the regeneration of the π -stacked 3D structure. Finally, the characterization of the regenerated π -stacked **2D-Co-MOF** has been completed with Elemental Analysis and ICP which confirm the same bulk composition of the regenerated material (Table S3).

To the best to our knowledge, this is the first time that MOFs have shown a “memory effect” in delamination-pillarization process, which is well-known for the most famous 2D material such as hydrotalcites.⁷²

On the other hand, to assess the suitability of the so-developed **2D-Co-MOF** as electrocatalyst, we produce a composite by its dispersion in an alcoholic Nafion solution (**2D-Co-MOF@Nafion**), which is a commonly used polymer in OER electrocatalysis.⁷³ The influence of Nafion on the chemical stability of the π -stacked 3D structure of the MOF in water was also investigated by means powder X-ray diffraction. From the comparison of the PXRD spectra of the **2D-Co-MOF** measured before and after its treatment with water for different contact times (Figure S13), it was found that the π -stacked **2D-Co-MOF** adopts a preferential [100] orientation in the composite, where the crystals of the MOF interact in a planar way with the Nafion. In addition, in the presence of an aqueous solution, the 3D structure of the MOF only lasted about 40 minutes before suffering the delamination process. Thus, Nafion slows down the pyridine-water exchange, but does not preclude it.

In addition, we have found that the current **2D-Co-MOF@Nafion** composite shows good adherence to graphite electrodes and long chemical stability for its application in promoting the electrocatalytic water oxidation reaction (*vide infra*).

Interplay between Redox Electrochemistry and Coordinative Chemistry of 2D-Co-MOF@Nafion composite.

We first investigated the electrochemical redox conversion of the **2D-Co-MOF@Nafion** composite in the absence of water by measuring the voltammetric response of a pyrolytic graphite electrode coated with the MOF composite in an acetonitrile solution containing 0.1 M [Et₄N]PF₆. As shown in Figure 4a, its electrochemical response is characterized by two pair of voltammetric waves located at 0.65 V (wave I) and 1.38 V (wave II) vs. NHE, that corresponds to the Co(II)/Co(III) and Co(III)/Co(IV) redox conversions, respectively.³⁸

Electrochemical Activation in Aqueous Solutions. In an aqueous 0.1 M sodium phosphate buffer solution at pH 7, observation of a significant cobalt redox conversion requires electrochemical activation of the so-modified electrode by applying a positive enough potential of 1.2 V (vs. NHE) for at least 30 minutes, as evidenced by comparing the voltammograms

measured before (blue line) and after (red line) electrochemical activation (Figure 4b). As described above, the presence of the Nafion in the **2D-Co-MOF@Nafion** composite slows down the pyridine-water exchange, but does not preclude it. According to this finding, the cobalt centers of the delaminated **2D-Co-MOF@Nafion**-modified electrode equilibrated in the aqueous buffer solution are coordinated axially to water molecules. Thus, the initial electro-inactivity can be tentatively ascribed to a limitation of the ionic migration across the film that is required to compensate the interfacial charge developed during the redox conversion of the cobalt centers. This limitation may originate from the compactness of the hydrophobic domains of Nafion. To probe this possibility, we have measured the voltammetric features of distinct **2D-Co-MOF@Nafion** composites differing in the Nafion content (Figure S21), observing that an increase of the Nafion content attenuates the incipient voltammetric features associated with the redox conversion of the cobalt centers and the OER. This finding corroborates the initial blocking properties of the Nafion film and suggests that the enhancement of the electrocatalytic current during the electrochemical activation of the composite might result from a decompaction of the film. On the other hand, for the electrochemically activated electrode, only the first cobalt voltammetric wave (at ca. 1.04 V vs. NHE) is well resolved due to concomitant contribution of the exponentially increasing electrocatalytic current associated with the oxygen evolution reaction. Bearing in mind that the electrocatalytically active species are the Co(IV)-oxo or Co(III)-oxyl radical,^{56,63,74} the proximity of the OER current to the cobalt voltammetric wave indicates that formation of above species is favored in aqueous solution with respect to the formation of Co(IV) in acetonitrile. To get more information of the cobalt-mediated electrocatalytic oxidation of water, we measured the voltammetric response of the **2D-Co-MOF@Nafion** composite for different acetonitrile/water ratio by adding variable volumes of an aqueous sodium phosphate buffer at pH 7 to the initial acetonitrile solution in the electrochemical cell (Figure S22). The increase of the exponential-like voltammetric feature located at $E > 1.3$ V (vs. NHE) with the water content clearly indicates that it corresponds to the electrocatalytic oxidation water. On the other hand, the small hysteresis between the forward and backward currents reveals that the electrocatalytic process is partially limited by water diffusion,

since otherwise either a sigmoidal (absence of mass transport control) or peaked (full mass transport control) voltammetric feature is expected.^{75,76}

Furthermore, analysis of the scan rate dependence of anodic wave I (Figure S23) reveals that the Co(II)/Co(III) redox conversion is fast for low scan rates (ca. $< 0.5 \text{ V s}^{-1}$, surface confined behavior) and becomes limited by the charge transport across the film for higher scan rates (diffusion-like behavior).

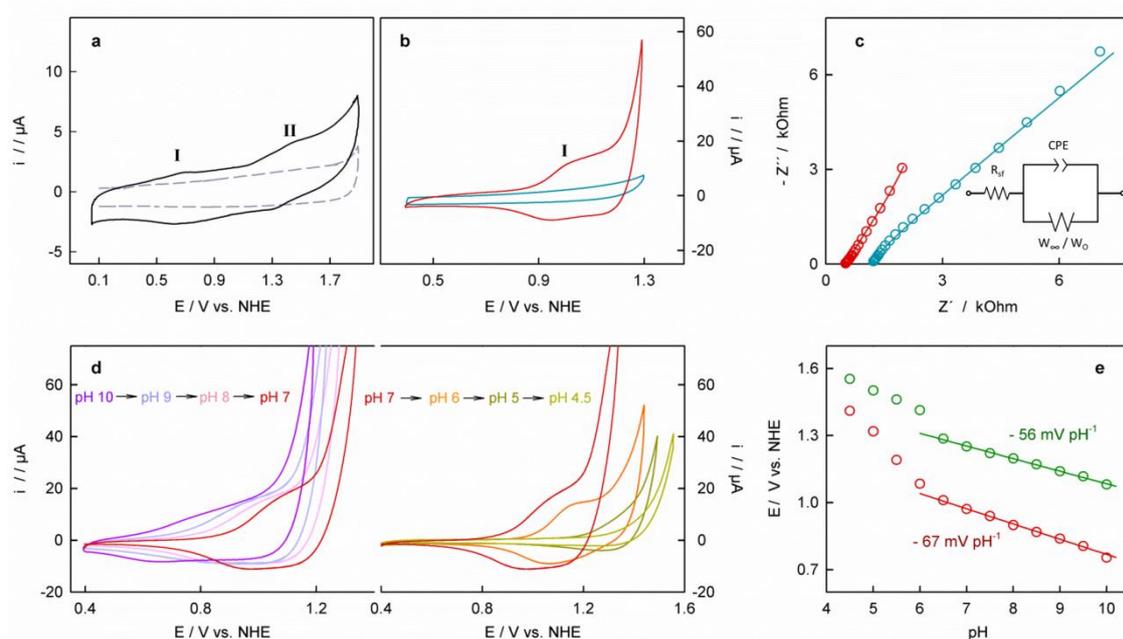


Figure 4. a) Cyclic voltammogram of a pyrolytic graphite electrode modified with Nafion (grey dashed line) or with **2D-Co-MOF@Nafion** (black line) recorded at 0.05 V s^{-1} in acetonitrile. b) Cyclic voltammograms recorded at 0.05 V s^{-1} in aqueous 0.1 M SPB solution pH 7 at $25 \text{ }^\circ\text{C}$ before (blue line) and after (red line) electrochemical activation of **2D-Co-MOF@Nafion** deposited in a pyrolytic graphite electrode and c) corresponding Nyquist plots measured at 1.1 V vs. NHE , before (blue symbols) and after (red symbols) electrochemical activation. Solid lines are the best fits using the equivalent circuit of the inset plot with the parameter values reported in Table S5. d) Cyclic voltammograms of a pyrolytic graphite electrode modified with **2D-Co-MOF@Nafion** recorded at 0.05 V s^{-1} and $25 \text{ }^\circ\text{C}$ in the electrolytes buffered at the indicated pH and e) corresponding E vs. pH plot estimated at $8 \text{ } \mu\text{A}$ (red symbols) and $40 \text{ } \mu\text{A}$ (green symbols).

To get more insights into the effect of the electrochemical activation, electrochemical impedance spectra (EIS) of the immobilized **2D-Co-MOF@Nafion** composite were measured at 1.1 V (vs. NHE) before and after its electrochemical activation (Nyquist plots in Figure 4c). Before the electrochemical activation (blue symbols), the EI spectrum shows the typical shape expected for a diffusion-controlled redox process with a limiting linear segment of slope ~ 1 in the low frequency region (high Z' values). This spectrum was quantitatively reproduced (solid line) with the equivalent circuit depicted in the inset of Figure 4c, where R_{sf} stands for the solution and film resistance, CPE for the constant phase element, and W for the semi-infinite diffusion Warburg element (optimum fitting parameter values reported in Table S5, Figures S24-S25). After electrochemical activation, the x-intercept of the spectrum (equals to R_{sf}) shifted toward a lower Z' value, which reveals an increase of the ionic migration rate across the MOF, and the low-frequency region shows an upward curvature, which is typical of a finite diffusion-controlled electron transfer across the film.⁷⁷⁻⁸¹ This spectrum was quantitatively reproduced by the equivalent circuit depicted in the inset of Figure 4c, provided that the semi-infinite diffusion W element was replaced by the finite-diffusion element with a totally reflecting boundary W_o (optimum fitting parameter values reported in Table S5). The change from semi-infinite to finite diffusion is consistent with an increase of the electron transfer rate across the film. Overall, these results reveal that electrochemical activation facilitates both ionic migration and electron transfer across the Co-MOF composite.

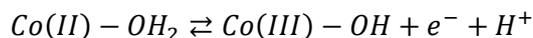
To explore whether the electrochemical activation leads to structural and/or coordinative changes, we have measured the Raman, PXRD and XPS spectra, as well as the FESEM and FIB images and EDX analysis of the composite before and after its electrochemical activation at 1.2 V (vs. NHE) for different exposition times, where extensive OER takes place. The insensitivity of the Raman and PXRD spectra (Figures S16 and S17) to the electrolysis time reveals that the cobalt centers maintain their coordination sphere and the individual nanosheets preserve their double layer structure during their electrochemical activation. XPS spectra (Figure S18 and Table S4) corroborate these findings and also reveal that electrochemical activation does not affect the

oxidation state of the cobalt centers in their resting state Co(II), where the presence of CoO_x has not been detected. On the other hand, FESEM and FIB images (Figures S19 and S20) as well as the EDX analysis (Figure S19) clearly show that cobalt centers are homogeneously distributed in the composite, thus ruling out metal aggregation. These results reveal that delaminated double nanosheets retain their crystallinity and morphology during extensive OER.

Altogether, these findings suggest that the enhancement of the electrocatalytic activity during the electrochemical activation of the composite might originate from an increase of the ionic permeability of the film, as evidenced by a decrease of its electrical resistance determined by electrochemical impedance spectroscopy, rather than from induced structural changes. In this line, we speculate that the generation of oxygen microbubbles during electrochemical water oxidation might contribute to the formation of microchannels in the film that facilitates the accessibility of the electrolyte to the cobalt centers.

Mechanistic Insights. The exchange of pyridine ligands by water molecules is expected to facilitate charge compensation in the electrochemical oxidation of the cobalt centers by ionization of the corresponding water-derived ligands. To probe this issue and provide a more complete redox speciation of the immobilized **2D-Co-MOF**, we have studied the effect of the solution pH on its voltammetric response by using sodium phosphate buffer (Figure 4d). It should be noted that the **2D-Co-MOF@Nafion**-modified electrode was equilibrated in the aqueous buffer solution, so that the starting cobalt species was Co²⁺(OH₂). Starting with an electrochemically activated **2D-Co-MOF@Nafion** in a 0.1 M SPB solution of pH 10, a decrease of the solution pH resulted in the shift of the cobalt voltammetric wave toward more positive potentials with a slope of ca. -60 mV/pH up to pH 6.5 (Figure 4e). This linear dependence is typical of a redox conversion involving a proton-coupled electron transfer with the same number of exchanged protons and electrons. Bearing in mind that the pK_a value of the water molecule coordinated to Co(III) in molecular complexes is within the range 5 – 7,^{65,82,83} and that of water coordinated to Co(II) in polyoxometalates is greater than 10,^{61,84} the above pH dependence is consistent with a

deprotonation of the coordinating water molecule upon oxidation of the Co(II) centers accordingly to:



Below pH 6.0, a progressive, irreversible loss of the cobalt voltammetric wave occurs until it disappears at pH < 5. The concomitant decrease of OER current corroborates the catalytic role of the cobalt centers. Bearing in mind that the pK_a values of the two carboxylic acid substituents of the bda ligand are 1.5 and 3.0,⁸⁵ and the pK_a values of the two pyridyl nitrogens of 2,2'-bipyridine are 1.8 and 4.5,^{86,87} the irreversible loss of the electrochemical activity can be ascribed to the MOF breakdown induced by protonation of the bda acid/base groups.

The voltammetric branch associated with the electrocatalytic oxidation of water shifts with the solution pH in a similar way to the cobalt voltammetric features (green symbols in Figure 4e), indicating that the cobalt-mediated electrocatalysis of OER proceeds through a series of proton-coupled electron transfer with the same number of exchanged electrons and protons.

Based on the above electrochemical and spectroscopic results, the following mechanism for the redox conversion and electrocatalytic water oxidation involving the **2D-Co-MOF@Nafion** composite in aqueous solution is proposed (Figure 5). First, electrochemical oxidation of the cobalt centers (Co²⁺-OH₂, **1**) at ~1.04V vs. NHE is accompanied by ionization of the water ligand to produce Co³⁺-OH (**2**) via a proton-coupled electron transfer (PCET). Then, a second PCET at a somewhat more positive potential is expected to produce the oxo-intermediate Co⁴⁺=O (**3**), which has a significant Co³⁺oxyl radical character (Co³⁺-O•, **4**), that has been recognized to be the catalytically active species for OER. From the different mechanisms proposed for the cobalt-mediated O-O bond formation,⁵⁵⁻⁶¹ direct coupling between two Co⁴⁺=O (or Co³⁺-O•) moieties of the same nanosheet is discarded because of the large Co···Co distance (4.69 Å). The lack of a second water-derived ligand in the cobalt centers rules out the geminal coupling. On the other hand, the increase of the film ionic permeation during the electrochemical activation of the composite indicates that the OER electrocatalysis requires a good accessibility of the electrolyte

to the cobalt centers that is fulfilled if delaminated nanosheets are well separated from each other. However, this scenario does not favor the inter-sheet radical coupling mechanism as it requires quite small inter sheet distances for the formation of the corresponding dinuclear moiety. This situation contrasts to that found in cobalt oxide, where the radical coupling mechanism is a realistic scenario as it involves two surface oxo bridged cobalt centers with good accessibility for the electrolyte. Since for the current system the above two requirements (proximity and electrolyte accessibility) cannot be simultaneously fulfilled, the more plausible scenario for the OER mechanism is the mononuclear water nucleophilic attack to $\text{Co}^{4+}=\text{O}$ or $\text{Co}^{3+}-\text{O}^\bullet$ to produce the hydroperoxide intermediate $\text{Co}^{3+}-\text{O}-\text{OH}$ (**5**) via a PCET, that may be facilitated by the bipyridine equatorial ligands as in the case of the highly efficient cobalt porphyrins.⁶² Finally, intermediate **5** reacts with water to form the oxygen molecule and regenerate the resting state of cobalt $\text{Co}^{2+}-\text{OH}_2$ through another PCET.

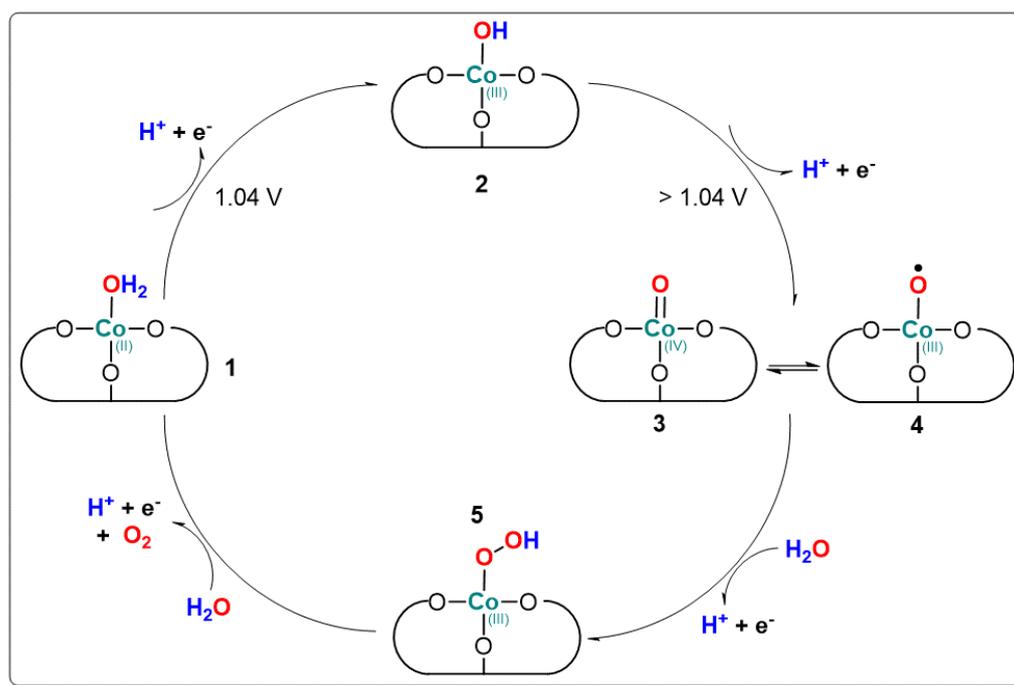


Figure 5. Proposed mechanism for the electrocatalytic oxygen evolution reaction mediated by **2D-Co-MOF** at neutral pH.

Benchmarking the Electrocatalytic Performance of 2D-Co-MOF@Nafion Composite for the Water Oxidation Reaction.

In order to assess the electrocatalytic activity of **2D-Co-MOF@Nafion** composite toward the OER at neutral solution steady state polarization curves were measured by means of rotating disk voltammetry. Figure 6a depicts the polarization curves recorded at neutral media with **2D-Co-MOF** and the typical OER electrocatalysts RuO₂, IrO₂ and Co₃O₄, all of them co-deposited with Nafion onto a graphite electrode. The electrocatalytic onset potentials were 1.73, 1.65, 1.77 and 1.84 V vs. RHE for **2D-Co-MOF**, RuO₂, IrO₂ and Co₃O₄, respectively. The corresponding overpotential values at 2 mA cm⁻² were 548, 404, 680 and 595 mV, for **2D-Co-MOF**, RuO₂, IrO₂ and Co₃O₄, respectively. Note that the overpotential value of **2D-Co-MOF** is similar to the values reported for the most active cobalt-MOF based catalysts at pH 7 (Table S6).

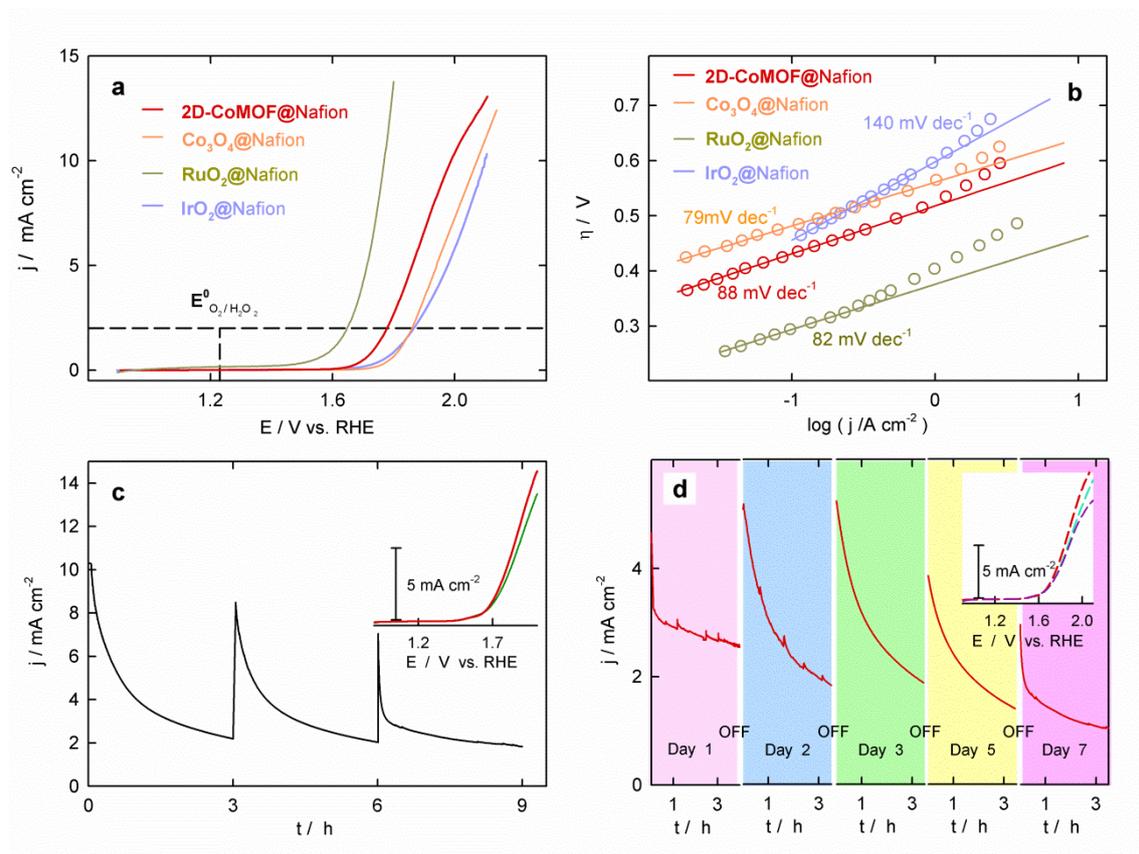


Figure 6. a) Rotating disk voltammograms recorded at 5 mVs⁻¹ and 1500 rpm and b) steady state Tafel plots of a pyrolytic graphite electrode modified with the indicated electrocatalyst in a 0.1 M SPB solution pH 7 at 25 °C. c) Consecutive chronoamperograms at 1.8 V vs. RHE for a **2D-Co-MOF@Nafion** modified graphite electrode in an aqueous 0.1M SPB solution pH 7 at 25 °C. Inset plot: Rotating disk voltammograms

measured at 5 mVs⁻¹ before (red line) and after (green line) the chronoamperometric experiment. d) Chronoamperograms at 1.8 V vs. RHE for a **2D-Co-MOF**@Nafion modified graphite electrode in an aqueous 0.1M SPB solution pH 7 at 25 °C for several on/off reaction cycles. Inset plot: Rotating disk voltammograms measured at 5 mVs⁻¹ after catalytic run at day 1 (red line), day 3 (green line) and day 7 (purple line).

The kinetics of the electrocatalytic OER mediated by the different electrocatalysts was assessed from the corresponding Tafel plot (Figure 6b) obtained from the chronoamperometric steady state current density data measured for a sequence of 0.01 V potential steps. **2D-Co-MOF** exhibits a Tafel slope (TS) value of 88 ± 4 mV decade⁻¹, which is similar to those obtained with RuO₂ and Co₃O₄ and lower than that of IrO₂. To the best of our knowledge, this is the best value among known cobalt MOFs catalysts operating at neutral media. The turnover frequency number (TOF) was determined from the expression $TOF = i/4Q$ (where i is the current intensity at a given overpotential and Q is the faradaic charge under the baseline-corrected voltammetric peak preceding the electrocatalytic branch). A value of 0.034 s⁻¹ was obtained for the TOF number of **2D-Co-MOF** at an overpotential of 400 mV with $Q = 2.5 \cdot 10^{-5}$ C (that corresponds to $2.6 \cdot 10^{-10}$ mol of electroactive cobalt). It should be remarked that this TOF value is superior to those reported for similar electrocatalysts²⁷ (Table S6). The effect of the amount of electroactive **2D-Co-MOF** on the OER electrocatalysis has been also evaluated (Figure S26). An increase of the electroactive cobalt population, obtained by increasing the electrochemical activation time, results in an increase of the electrocatalytic current density at a given potential and a decrease of the corresponding overpotential at a given current density. However, the TOF number determined at an overpotential of 400 mV decreases upon increasing the electroactive population until it levels off at ~ 0.035 s⁻¹ for an electroactive population of $2.0 \cdot 10^{-10}$ mol. This dependence reveals that not all cobalt centers catalyze the water oxidation reaction at the same level.

The improved activity for water oxidation reaction of the **2D-Co-MOF**@Nafion composite electrocatalyst can be ascribed to both a more efficient charge transport across the catalyst film and a facilitated water nucleophilic attack to the active centers presumably by the presence of nitrogen-containing aromatic equatorial ligands.

The operational stability and long-term durability of the electrocatalyst during the OER have also been explored. First, the chronoamperometric current for the **2D-Co-MOF@Nafion**-modified graphite electrode was measured at 1.8V (vs. RHE) for three consecutive water electrolysis cycles that lasted 9 h (Figure 6c). The chronoamperograms are characterized by an initial decrease of the current that can be ascribed to the formation of oxygen bubble at the electrode surface, thereby affecting the water transport inside the multilayered film (Figure S27). Then, the current approaches a steady state value of $\sim 2 \text{ mA cm}^{-2}$ in each chronoamperogram, with a negligible decrease in the current density at the end of the 9 h of operation. The similarity of the polarization curves of fully activated **2D-Co-MOF@Nafion** measured before and after the water electrolysis experiment, depicted in the inset plot of Figure 6c, reflects the high stability of this material. Moreover, a faradaic efficiency value of 77% of **2D-Co-MOF** for OER reaction was determined after extensive water electrolysis, reflecting that the current density mostly originates from water oxidation. Additionally, the analysis of the electrolytic solution after extensive water electrolysis by UPLC-HRMS (Q-ToF), reveals the presence of small amount of pyridine and Nafion (Figure S15), which is consistent with the aforementioned pyridine-water ligand exchange and with a certain composite peeling off during water electrolysis. It should be noted that the solution pH remains unchanged during water electrolysis.

The recyclability of the catalyst has also been examined along several successive catalytic runs with on/off cycles that lasted 7 days, checking its resistance to activity loss. As can be seen in Figure 6d the current density decreases by 50% after five recycling along 7 days. However, the rotating disk voltammograms recorded after each catalytic run reveal that **2D-Co-MOF@Nafion** composite retains a remarkable electrocatalytic performance without significant activity loss (inset plot in Figure 6d).

Overall, the long-term stability of delaminated **2D-Co-MOF** in the composite is consistent with the absence of significant structural changes of the composite during extensive OER, as described in the previous section.

Conclusions

In summary, the synthesis of a new cobalt MOF based on two layered core that are strongly connected by intermolecular bonds has been developed. The use of a well-defined cobalt cluster as starting compound for the synthesis directs the construction of a Co-MOF with an unusual topology. In this MOF, the layered double nanosheets are held together by π - π stacking interactions between labile pyridine ligands. It has been shown that this material delaminates in the presence of water, and that the original 3D layered structure can be regenerated by solvothermal treatment with pyridine, so that the individual nanosheets have associated memory.

Dispersion of the so-synthesized MOF in an alcoholic Nafion solution gives rise to a composite (**2D-Co-MOF@Nafion**) with good adherence to graphite electrodes and long-term chemical stability. Electrochemical activation of the **2D-Co-MOF@Nafion**-modified electrode improves ionic migration and electron transfer across the film, and promotes the formation of electrocatalytically active cobalt centers. The activated composite exhibits enhanced electrocatalytic activity for water oxidation in neutral media, with a TOF value and robustness superior to those reported for similar electrocatalysts operating under the same experimental conditions. Based on the particular topology of the new Co-MOF, with quite distant cobalt centers, and its spectroscopic and electrochemical characterization, a reaction pathway relying on mononuclear centers is proposed for the cobalt-mediated electrocatalytic OER. Its high electrocatalytic efficiency at neutral pH is tentatively attributed to the presence of nitrogen-containing aromatic equatorial ligands that presumably facilitate the water nucleophilic attack as in the case of cobalt porphyrins.

Associated Content

The Supporting Information is available free of charge on the ACS Publications website.

Experimental details. Synthesis and characterization of the **2D-Co-MOF** (X-ray diffraction, thermogravimetric analysis, adsorption measurements, and chemical stability). Crystallographic data for **2D-Co-MOF** (CCDC 1994492, CIF). Characterization of the electrochemically activated **2D-Co-MOF@Nafion** composite (X-ray diffraction, Raman spectra, XPS spectra, FESEM images and EDX analysis). Additional electrochemical characterization of **2D-Co-MOF@Nafion** composite (voltammetric features and quantification of the electrochemical impedance spectra).

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Notes

The authors declare no competing financial interest.

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