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Metal–Organic Framework/GO Electrocatalysis for Water Splitting: Oxygen Evolution Reaction and Hydrogen Evolution Reaction: A Comprehensive Review

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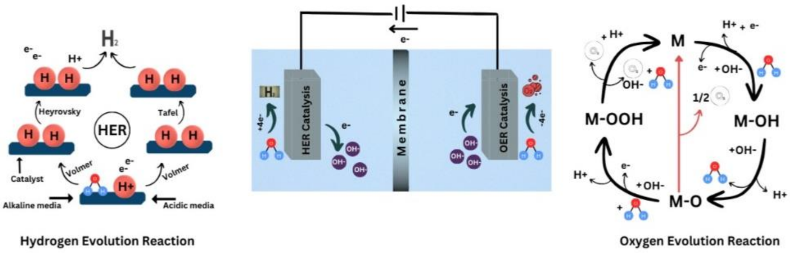
ABSTRACT

An intriguing concept for creating cutting-edge sustainable energy solutions is the de novo engineering of reticular metal-organic frameworks on top of graphene-based materials. Graphene and its derivatives function as metal-organic framework structuring agents, giving them intriguing morphological, textural, topographical, geographical, interfacial, chemical, electrical, and mechanical properties, thanks to their multifunctional lattice and flat yet flexible sheet structure. The metal-organic framework/graphene-based hybrids' synergistic advantages made them competitive substitutes for costly noble metal-based catalysts. Despite developments, metal-organic framework/graphene-based nanocatalysts for hydrogen evolution processes were not the main focus of any of the earlier reviews. As providing an overview of the development of hybrid nanocatalysts for hydrogen production, this review seeks to close this knowledge gap. It demonstrates how metal-organic framework catalysts are superior to traditional materials for producing hydrogen and explains why hybridizing pure metal-organic frameworks with graphene and its derivatives broadens the spectrum of hydrogen evolution reactions. Additionally, it summarizes the methods of preparation, looks at distinguishing characteristics, and thoroughly assesses the hydrogen evolution reaction and oxygen evolution reaction performance of the metal-organic framework/graphene-based hybrid electrocatalysts that have been published at this point. Lastly, it reveals the present state, current obstacles, and possible future developments of these hybrids based on metal-organic frameworks and graphene.



INTRODUCTION

A pollution-free environment in the current era depends on the production of clean, renewable, and sustainable energy. More than 80% of our energy output still comes from fossil fuels, despite the fact that the need for energy is growing yearly due to our growing population [1, 2]. The environment is seriously threatened by greenhouse gas emissions, pollution, and global warming, which are all caused by burning fossil fuels [3, 4]. Over 70% of the Earth's surface is made up of the water, which has enormous potential as a source of renewable energy. Through water energy, ocean energy often referred to as "blue energy" is a substantial renewable power source [5-7]. Utilizing this water-based energy, hydrogen (H_2), a possible substitute for fossil fuels that helps the environment by enabling high energy production under moderate pressure and temperature conditions, is produced [8-11]. The hydrogen is one of the most abundant and high-energy resources in the cosmos, there has been a significant increase in investment in its production in recent years. From energy capture to production, its adaptability covers a broad spectrum of applications. The fact that hydrogen burns cleanly and emits no pollutants, especially greenhouse gases, is arguably its greatest benefit. Numerous studies on water splitting using electrocatalysts have been conducted. Included are the two half-cell reactions: the cathode creates hydrogen through hydrogen evolution reactions (HER), and the anode produces oxygen through oxygen evolution reactions (OER). Depending on the electrolyte's needed medium, these two surface reactions occur [12-14].

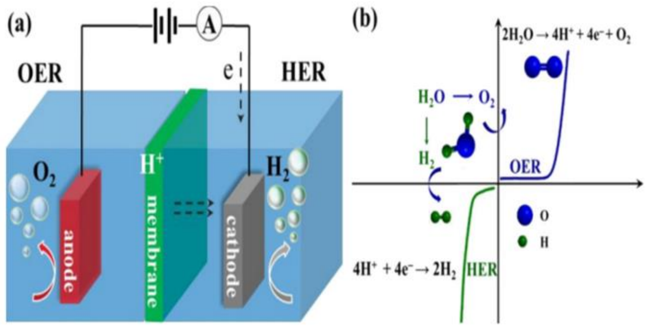
It's important to carefully choose the right electrocatalysts, the water-splitting hydrogen generation process can be enhanced. In electrochemical cells for water splitting, electrocatalysis has been crucial in removing kinetic energy barriers. Originally, the costly noble metals (Pt, Pd, and Ru) were employed for efficient electrocatalytic hydrogen generation [15, 16]. To reduce the use of noble metals, however, cost-effective, stable, and sustainable water-splitting materials must be used due to their limited supply. It seems that there are now more options for enhancing water electrolysis thanks to the development of composites and hybrid catalysts. Metal-organic framework (MOF) composites are used as substitutes for noble metals because of their higher active sites, wide surface area, porosity, and crystallinity. MOFs are organic-inorganic hybrid materials that are crystalline and porous, having organic linkers encircling core metal ions that are positively charged [17]. MOFs have recently emerged as a key component of carbon capture, fuel cells, supercapacitors, and photochemical as well as electrochemical reactions for overall water splitting (HER and OER) production of hydrogen. Designable structures with a high surface area, wide surface channels, and potential catalytic active sites are characteristics of MOFs. They fall into three main categories: pristine MOFs, MOF-based composites, and MOF-derived composites. For the creation of water-splitting hydrogen utilizing photocatalysts, electrocatalysts, and photo-electrocatalysts, pure MOF is the subject of extensive research and reviews [15, 18]. On the other hand, virgin MOFs along with basic MOF-based materials exhibit restricted pore accessibility, selective surface functionalization, and decreased stability. Recent study has been using metalorganic frameworks (MOFs) with graphene oxide (GO) materials due to the fact that these materials possess greater mechanical strength, large surface area, stability, increased chemical functionality, and adjustable porosity in comparison to pure MOF and simple MOF-based composites. This will contribute to an increase in the generation of hydrogen [19, 20]. Graphene is a network of single-layered carbon atoms arranged in a two-dimensional hexagonal pattern that mimics the layered structure of a honeycomb crystal. Graphene has exceptional mechanical strength, transparency, surface modification, and heat conductivity. Because of these characteristics, it stands out among the other newly researched materials of the twenty-first century as an emergent nanomaterial [3, 20]. There are three different forms of graphene: reduced graphene, graphene oxide, and pristine graphene. Solar cells, fuel cells, energy storage devices, and medicinal devices are just a few of the many scientific uses for graphene. When added to composite materials, graphene exhibits greatly improved qualities and functions as a pseudocapacitive material. When graphene oxides are combined with MOF in MOF-GO materials, their activity is increased and new possibilities for energy storage, catalysis, and environmental sustainability become apparent [21].

Numerous comprehensive studies on improving environmental sustainability have been published in recent years. Although virgin metal-organic frameworks, MOF-based materials, or MOF-derived materials have been the subject of numerous reviews, MOF-GO-based and derived materials are currently becoming important participants in overall water splitting [1, 22, 23]. Based on previous research and existing literature, this work provides a comprehensive analysis of the present importance of MOF-GO-based and derived materials as electrocatalysts for overall water splitting. Particular attention is paid to the role of HER and OER in the creation of hydrogen. The roadmap for this study emphasizes the significance of electrocatalysts in water splitting, draws attention to materials based on MOF, and highlights the present successes in the development of MOFGO-based and derived materials for the purpose of increasing hydrogen generation via water splitting. The reason why the writers chose this subject for their study was because of the significance of MOF-GO-based materials in sustainable energy solutions and the evolving role that these materials play in the field.

Plausible Mechanism of Electrocatalysts for OER and HER Water Splitting

The special area of electrochemistry known as "electrocatalysis" is primarily concerned with the kind of catalyst that is employed to accelerate electrochemical processes. Developments in electrochemistry, particularly in fuel cells and electrocatalytic cells, have been essential in recent decades for the creation of a sustainable environment and energy conversion. Electrochemistry methods use electricity to power energy-intensive processes such water electrolysis in hydrogen fuel cells, nitrate conversion reactions, and carbon dioxide to hydrocarbon conversion. As water is electrolyzed, oxidation occurs at the anode to produce oxygen gas, while proton reduction at the cathode produces hydrogen gas. Water and electrical energy undergo chemical oxidation-reduction as a result of the entire reaction. When water is reduced during the HER process, two essential processes for water splitting which lead to the formation of hydrogen gas (H_2) and hydroxide ions (OH) at the cathodic end [24]. Water (H_2O) and oxygen gas (O_2) are produced by the oxidation of hydroxide ions at the anode in the OER mechanism. Furthermore, a polarization curve for HER and OER is visible in the half-reaction of water electrolysis, particularly in an acidic media. Although the mechanisms vary significantly depending on the environment, the oxygen evolution reaction in neutral and acidic environments proceeds according to a series of proton-coupled electron transfer (PCET) phases [21, 25, 26].

Figure 1



An outline of the general water splitting experimental setup. (a) The polarization curve and half-reaction of water dissociation in an acid electrolyte; (b) The graphical depiction of H2 and O2 creation from water dissociation. Reproduced with permission from Ref. [26]. Copyright 2020. The Royal Society of Chemistry.

Water in a neutral media A hydroxyl intermediate (M–OH) is created when molecules adsorb onto the catalyst surface. This intermediate is then deprotonated and oxidized to an oxo species (M = O). This intermediate oxo forms a hydroperoxo species (M–OOH) when it combines with water, eventually releasing oxygen (O_2) and regenerating the catalytic site. In neutral conditions, buffering species are essential for stabilizing intermediates and promoting proton elimination [16, 27]. The reaction proceeds through comparable intermediates in acidic media as well, beginning with the adsorption of a water molecule to generate $M–OH_2^+$. The M = O and M–OOH intermediates that are created as a result of successive PCET operations release oxygen and regenerate the active site. Proton transfer kinetics are improved by the acidic environment, but stable catalysts like IrO_2 or RuO_2 are needed to withstand corrosion and preserve stability in hostile environments [28]. For better OER performance, both methods highlight the significance of effective catalyst design and intermediate stabilization. There are three main ways that HER happens in an alkaline medium: the Volmer step, which uses electrochemical reduction of water to create adsorbed hydrogen atoms (H) and hydroxide ions (OH^-); the Heyrovsky step, which combines H with another water molecule to release molecular hydrogen (H_2); or the Tafel step, which combines two H atoms to directly form H_2 [29]. With slower kinetics than acidic media, the alkaline environment presents difficulties that need for catalysts with significant water-splitting and hydrogen adsorption/desorption properties [30]. These processes emphasize how important intermediate species are and how sophisticated electrocatalysts are required for effective water splitting reactions.

Factors Affecting OER and HER Electrocatalytic Water splitting

In this electrochemical water splitting has been performed to produce hydrogen and oxygen with high efficiency, it is crucial to comprehend and optimize the variables affecting electrocatalytic performance. To guarantee quick reaction kinetics, high catalytic activity, and stable operation in a range of circumstances, electrocatalysts need to have certain characteristics. The efficiency and stability of electrocatalysts in HER and OER are directly impacted by a number of critical parameters, including surface area, overpotential, pH, and Tafel slope. Researchers can improve overall system efficiency, lower energy input requirements, and speed up reaction times by examining and refining these variables [31, 32]. A thorough explanation of each component and its function in electrocatalysis is provided below:

Surface Area

The electrocatalysts surface area has a significant impact on the material's thermal stability, catalytic activity, and accessible active sites in an electrochemical process. The increase in surface area naturally improves the interaction between the catalyst's active sites. On the other hand, the supporting material's greater surface areas promote intrinsic activity, preserve electrical conductivity, prevent agglomeration, and uniform dispersion of nanoparticles.

Overpotential is an important but difficult component of electrocatalytic HER and OER water-splitting hydrogen generation. One important factor is the reduced overpotential value. It can be decreased by stabilizing the intrinsic characteristics of electrocatalysts and concentration polarization, even though it is difficult to maintain.

pH

The pH of electrolytes has a significant impact on the available electrolyte source, operating circumstances, and electrocatalysts selection [33, 34]. As it reduces operating costs and guarantees smooth electron transfer dynamics at varying current densities, maintaining the pH in both acidic and alkaline media is essential.

Tafel Slope

The Tafel slope is one of the most important variables in electrocatalysis. It provides crucial information about the kinetics, effectiveness, and reaction mechanism of the electrocatalysts [35, 36]. Better electrocatalysts efficiency and reaction kinetics are indicated by a decreased Tafel slope value. The structural features and effectiveness of electrocatalysts for the generation of hydrogen and oxygen gas are also influenced by a few other factors.

MOFs and MOF-GO Composites for Electrocatalytic Water Splitting

The use of MOF-based electrocatalysts to increase the effectiveness of water splitting reactions has grown significantly in recent years. The fundamental metallic framework of MOF has been altered, various functionalizable linkers have been introduced, and extra metal atoms or substrates have been integrated into the MOF structure, among other electrocatalytic water splitting processes. According to this pattern, new MOF materials such as pure, bimetallic composites, MOF-based materials, and MOF-derived materials are emerging for electrocatalytic water splitting. Graphene oxide is added to a MOF to create a hybrid (MOF-GO) composite, which has a shape similar to nanosheets to enhance mass and electron transfer and provide significant exposure to catalytic active sites.

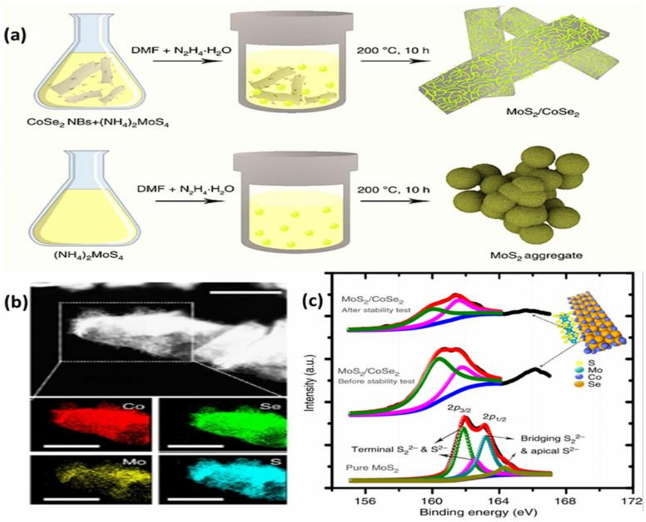
Mechanism of Electrocatalytic Water Splitting by MOF and MOF-GO Composites

The exceptional structural characteristics of MOFs, including their high porosity, specific surface area, functionalizable linkers, and programmable pore topologies, make MOF-based electrocatalytic water splitting essential. For absorbing water molecules onto the MOF electrocatalysts surface, this process facilitates the most directed method of producing hydrogen at a specific voltage of 1.23 V under typical conditions (25 °C and 1 atm). The electrocatalytic HER and OER water splitting of transition metal nitrides, carbides, phosphides, and sulphides is also economical and effective when the electrolytic system is appropriate. Additional metal atoms or substrates can also be added to electrocatalysts to improve their inherent electrocatalytic qualities. The electronic structures are modulated by this addition, enabling improved charge transfer and active sites in electrocatalysts to produce hydrogen and oxygen. Clean energy materials are synthesized to meet the world's sustainable energy needs. These days, graphene in the form of graphene oxides (GO) or reduced graphene (rGO) combined with metal-organic frameworks improves electrochemical performance through effective electron transfer, including active site exposure, catalyst dispersion, charge mobility, and stability [22, 37-39]. When GO is added, the electrochemical resistance decreases and the HER and OER exchange current density increases.

MOFs and MOF-GO HER Electrocatalysts

The development of more efficient electrocatalysts is essential for HER water splitting in a green environment [40, 41]. Several recent electrocatalysts that investigate the catalytic activities of the highly effective MOF and MOF-GO-dependent HER electrocatalysts listed in Table 1 have been mentioned. Jiang et al studied the electrodeposited nickel phosphorus (Ni–P) film that demonstrated had an impressive overpotential of -93 mV (at 10 mA/cm^2). The outstanding performance of Pt and IrO_2 is what causes the exceptional activity of Ni–P film [42]. Zheng et al. the nanofoam catalyst, which uses its trifunctional layer and has cobalt (Co/Se–MoS_2-NF) on the inner layer and selenium on the surface, exhibits the material's notable current density HER activity [43]. Cobalt atoms are contained in inner layers to activate nearby sulphur atoms, as indicated by the lower overpotential value of 382 mV. Dai et al. used a one-pot solvothermal approach for the hydrogen evolution process that demonstrated the chemical interaction to produce molybdenum polysulphide (MoS_x) implanted over a porous Zr-based MOF (Zr-MOF/UiO-66-NH_2). The stable electrolytic HER performance exhibits an exceptional Tafel slope in acidic circumstances, with 59 mV dec^{-1} and an overpotential of 200 millivolts [44]. These findings demonstrate the adaptability of Mo-based HER electrocatalysts, which provide quicker and less costly electrocatalysts that transport protons. Cobalt diselenide (MOF-$CoSe_2$) nanoparticles made from metal-organic frameworks can also be made by attaching the particles to nitrogen-doped graphitic carbon using the in-situ selenium of Co-based MOFs. The $MoS_2/CoSe_2$ hybrid catalyst, which was produced under the same 0.5 M H_2SO_4 conditions, has more substantial electrocatalytic performance than MOF-$CoSe_2$ [45]. The high-resolution STEM-EDX elemental mapping verified the important portion of the $MoS_2/CoSe_2$ hybrid catalyst. The binding energy XPS spectra overpotential of 68 mV indicates that $MoS_2/CoSe_2$ has strong HER performance, despite the synergistic action of molybdenum disulphide and cobalt diselenide materials. According to this, $MoS_2/CoSe_2$ has a higher active surface area and numerous active locations in the hydrogen evolution reaction's Volmer-Tafel pathway [46].

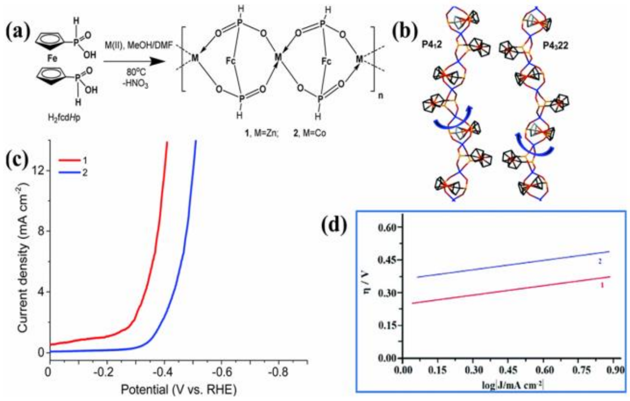
Figure 2



Impact of synthesis technique and structural features on the $MoS_2/CoSe_2$ hybrid catalyst's HER performance. (a) The $MoS_2/CoSe_2$ hybrid catalyst synthesis process; (b) STEM-EDX elemental mapping; (c) XPS spectra. Reproduced with permission from Ref.[46]. Copyright 2015. Nature Communications.

Li et al. investigate the impact of substituted halogen for electrochemical HER, found that halogen atoms increase the catalyst activity by desorbing hydrogen from cobalt sites through the synthesis of 2D polyhalogenated Co(II)-based MOF (Co–Cl4-MOF), which produced an 81% yield based on Cl4–H_2pta and a lower overpotential (283 mV). As an effective electrocatalysts [47]. Khrizanforova et al. synthesized a 3D Ni redox active MOF based on 4,4′-Bipyridine and Ferrocenyl Diphosphinate ligands for HER [48]. The kinetic characteristics of Ni-MOF HER are improved in both an organic and aqueous environment by the inclusion of a 4,4′-bipyridine linker. The electrochemical investigations show that Ni-MOF's exceptional endurance (about 10,000 cycles) and low overpotential of 350 mV contribute to its remarkable HER efficiency. Shekurov et al. created nanocatalysts based on the ferrocenylenbis (Hphosphinic) acid (H2fcdHp) ligand and the Zn nitrate salt, created a unique 1D helical Zn redox active coordinated ZnfcdHp polymer as an effective electrocatalysts for HER. The chirality (R-enantiomer, S-enantiomer) of the helical chain [49]. The hydrogen evolution reaction of the ZnfcdHp catalyst exhibits a 340 mV overpotential and a 110 mV dec^{-1} Tafel slope with a linear sweep voltammetry (LSV) polarization curve for prolonged stability. In hydrogen evolution processes, these catalysts were also thought to be better alternatives to Pt-catalysts. Roy et al. presented the metal-organic frameworks for effective hydrogen evolution catalytic activity made of cobaloximes-based catalyst UU-100(Co), which function as metallo-linkers in the clusters of hexanuclear zirconium [50].

Figure 3



The performance of the 1D Helical Znfcd*Hp* polymer is influenced by its synthesis and structural characteristics. (a) The synthesis method of the 1Dhelical Zn redox active coordinated ZnfcdHppolymer is graphically illustrated; (b) the chirality of the helical chains (R-enantiomer, S-enantiomer); and (c) LSV polarization curves with matching (d) Tafel slopes. Reproduced with permission from Ref. [49]. Copyright 2019. Royal Society of Chemistry.

MOFs and MOF-GO OER Electrocatalysts

Several metal-dependent electrocatalysts for electrochemical water splitting for oxygen evolution processes have been reported, as indicated in Table 1, depending on specific methodologies [51]. Jiang et al. shows a nickel-phosphorus (Ni–P) film electrodeposited impressive advancements for OER, with an overpotential value of 344 mV. High catalytic activity of the Ni–P film was credited with the improved OER performance. Maity et al. presented a $Ni_{0.2}Co_{0.8}P$, a nonporous bimetallic phosphide catalyst with a three-dimensional network structure and increased surface area [52]. Under alkaline OER conditions, the resultant catalyst $Ni_{0.2}Co_{0.8}P$ exhibits remarkable performance, with a Tafel slope of 44 mV dec^{-1} and an overpotential of 230 mV. These findings showed a three-dimensional network topology of the $Ni_{0.2}Co_{0.8}P$ catalyst and demonstrated a synergistic interaction between the d and p bands with quick mass transfer capabilities. Ni has very effective, long-lasting, and reasonably priced electrocatalysts that contribute to large-scale water splitting. Wang and colleagues demonstrated the synthesis of a hollow tricomponent metal phosphide using cobalt-containing MOFs (ZIF-67) and high-temperature reduction at a reduced overpotential value of 329 mV. The much improved water oxidation performance makes using MOFs as a precursor to create extremely efficient water-splitting electrocatalysts a flexible strategy. Xu et al. created ultrathin two-dimensional cobalt metal-organic framework nanosheets [$Co_2(OH)_2BDC$] using a straightforward hydrothermal surfactant-assisted technique. As a working electrode, the resulting 2D Co-MOFs were employed [29]. The electrodes LSV curves were seen at a slow scan rate of 5 mV s−1. Additionally, the 2D CoMOFs material exhibits a Tafel slope of 74 mV dec^{-1} in 1.0 M KOH and a low overpotential of 263 mV at 10 mA cm^{-2}. The LSV polarization curves and the Tafel slope of 74 mV dec^{-1} demonstrate the material's superior catalytic kinetics, which emphasize its capacity to target more active sites, leading to increased durability and better OER performance.

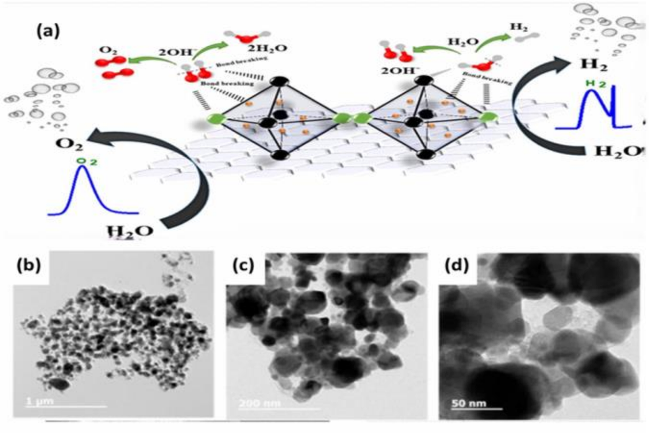
Table 1

Recent Studies on MOF/MOF-go for Electrocatalysts Water Splitting Hydrogen Production.

Catalysts	Electrolyte	Tafel Slope (mV dec^{-1})	Stability	Production	Reference
Ni-P	1 M KOH	43	24 h	H_2	[42]
Co/Se–MoS_2–NF	0.5 M H_2SO_4	67	360 h	H_2	[43]
Zr-MOF/UiO-66-NH_2	0.5 M H_2SO_4	200	7 h	H_2	[44]
MOF-$CoSe_2$	0.5 M H_2SO_4	42	2,000 cycles	H_2	[45]
MoS_2/$CoSe_2$	0.5 M H_2SO_4	36	24 h	H_2	[46]
Co–Cl4-MOF	0.1 M KOH	86	24 h	H_2	[47]
3D-Ni(fcd*Hp*)n	0.5 M H_2SO_4	350	10,000 cycles	H_2	[48]
Znfcd*Hp*	0.5 M H_2SO_4	110	1,000 cycles	H_2	[49]
UU-100(Co)	0.1 M $NaClO_4$	250	18 h	H_2	[50]
V-NixFey-MOF/GO	1 M KOH	97	Over 20 h	O_2	[52]
Co BTC-rGO	1 M KOH	71.4	3,600 s	O_2	[52]
Fe–Ni–P/rGO	1 M KOH	240	5 h	O_2	[29]
R@FeNi	1 M KOH	62	Over 1,000 cycles	O_2	[28]
3D Gr/Ni-MOF	0.1 M KOH	93	20 h	O_2	[21]

Abazari et al. used the solvothermal approach to describe a cost-effective Fe–Ni–P/rGO composite in an alkaline medium. They found a reduced overpotential of 264 mV with a Tafel slope of 62 mV dec^{-1}. Through its nonporous structure, the bimetallic FeNi catalyst's development promotes (-OH) transfer and demonstrates remarkable OER performance. Fang et al. employed an innovative and logical approach.by paralyzing and then phosphidating a bimetallic iron-nickel phosphide reduced graphene oxide (R@FeNi) composite [21]. The catalyst achieves a low overpotential value of 240 mV at a current density of 10 mA cm^{-2}, demonstrating improved OER activity. Additionally, the high conductance of the reduced graphene oxide in the R@FeNi composite results in outstanding OER kinetics with LSV curves and a Tafel slope (63 mV dec^{-1}) when compared to other non-noble MOFs. Xie and colleagues presented a new three-dimensional graphene oxide nickel-based metal-organic framework (3D Gr/Ni-MOF) composite that was created by using ultrasonic and freeze-drying processes.

Figure 4



Synthesis, OER performance, and structural description of the V-Ni$_x$Fe$_y$-MOF/GO catalyst. (a) Diagram of the synergistic pathway for creating the V-Ni$_x$Fe$_y$-MOF/GO catalysis; (b–d) TEM image. Reproduced with permission from Ref. [21] Copyright 2022. Elsevier.

CONCLUSION AND FUTURE PERSPECTIVES

The applications for nanotechnology in green energy generation and storage are numerous and include water splitting for hydrogen storage, batteries, fuel cells, supercapacitors, and biosensors. Green hydrogen production could benefit greatly from the use of nanomaterials in creative composite synthesis for improved structural qualities and effective energy use. Researchers have used amazing electrocatalysts, photocatalysts, and photoelectrocatalysts to advance hydrogen storage. Recent advancements in the application of MOF and MOF-GO-based electrocatalysts and their employment in electrocatalysis for the OER and HER are the main topic of this review. Highly conductive, stable, adjustable, and multipurpose materials are MOF-GO-based electrocatalysts. Graphene oxide sheets allow them to offer more active sites than conventional MOFs. In-situ growth, solvothermal, hydrothermal, and microwave-assisted processes have all been used to create MOF and MOF-GO-based material nanostructures. Promising materials for total water splitting, these techniques improve electrocatalytic performance through enhanced Tafel slope, stability, overpotential, surface area, current density, and charge transfer resistance. Covalent organic frameworks (COFs) with enhanced water-splitting properties are being developed by researchers. In order to create a green, sustainable environment, MOFs and MOF-GO-based materials provide unique future challenges in addition to their considerable potential. Prospects for MOF and MOF-GO materials as electrocatalysts in the future show encouraging avenues for increasing effectiveness and broadening applications.

Enhanced Conductivity: By altering their fundamental structures or adding conductive elements, future research should focus on creating highly conductive MOFs.

Structural Stability: It is crucial to create strong MOFs and MOFGO composites that are impervious to structural deterioration during catalytic operations.

Single-Atom Catalysts: By increasing the exposure of active sites, research into single-atom MOF based catalysts can optimize catalytic activity.

Computational Integration: The design and optimization of MOF and MOF-GO materials will greatly benefit from the application of computational methods such as machine learning and quantum chemistry.

Extension of Applications: MOFs and COFs present prospects in domains such as CO_2 reduction and artificial photosynthesis, in addition to electrocatalysis.

Electrical Conductivity: Compared to COFs, which have metallic and semiconducting characteristics, MOFs and their derivatives often have lower electrical conductivity.

In conclusion, creating affordable electrocatalysts is critical to solving environmental issues with energy storage, supercapacitors, batteries, and water splitting. Evaluating recent developments in MOF and MOF-GO materials for electrocatalytic water splitting is the main goal of this review.

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