

Recent advances on water electrolysis based on nanoscale inorganic metal-oxides and metal-oxyhydroxides for hydrogen energy production

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ABSTRACT

Hydrogen production through water electrolysis is a promising pathway to advance green energy technologies. The efficiency of cost-effective nanoscale electrocatalysts has been extensively studied over the past three decades, leading to significant advancements in catalytic nanostructure materials. Oxyhydroxide (OxH) electrocatalysts have gained attention for their robust performance in the hydrogen evolution reaction (HER) under alkaline conditions. This review explores recent developments in transition-metal-based HER and oxygen evolution reaction (OER) catalysts, including alloys, phosphates, oxides, hydroxides, and oxyhydroxides. Emphasis is placed on structural design, controlled synthesis, and performance enhancement strategies, providing insights into the mechanisms of water splitting. The study also discusses advancements in self-supported electrodes and highlights the applications, challenges, and potential of OxH-based materials for efficient energy production. By addressing global energy demands and environmental concerns, this work contributes to the development of hierarchical OxH nanostructures, offering a foundation for future water-splitting technologies.

1. Introduction

Generally, energy storage and conversion technologies have several practical uses in sectors such as electric autos, public transportation, and more traditional industries [1]. Many people are eager in knowing more about these technologies, and the number of individuals who are interested in learning more about them is growing. For the purpose of satisfying the ever-increasing demand for energy around the world, the creation of environmentally friendly energy storage and conversion technologies is an urgent and essential requirement. Electric power systems that is appealing for the generation of hydrogen through the electrolysis of water, which is harmless for the environment. The OER and the hydrogen evolution reaction are the reactions that are carried out on the anode and the cathode, respectively, in the process of water electrolysis [2,3]. Since their discovery, oxyhydroxides (OxHs) and

other oxides of metals have been the subject of a significant amount of research as possible electrocatalysts. The reason for this is because they have an exceptionally long cycle life, an extremely high energy storage capacity, a moderate energy density, a high power density, and an outstanding changeable valence statement [4,5]. It is because of these features that catalysts are one of a kind [6,7]. Within the scope of this article, you will acquire knowledge regarding the water-splitting reaction, oxygen evolution reactions (OER), and oxygen reduction reactions (ORR). Discover how these electrochemical processes take use of recent findings in metal-OxH composite materials, as well as the amount of energy that is required for each of these processes. More effective electrocatalysts based on OxH have been developed through the utilization of a variety of techniques, including hydrothermal (HT) treatments, sol-gel, template-assisted, and microwave-assisted methods [8, 9].

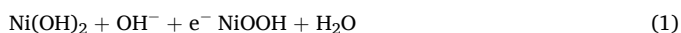
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The degree of difficulty that electrocatalysts may present in terms of handling is directly proportional to their size and shape. One of the most important applications of EC approaches is the creation of an OxH composite that is both stable and very efficient, and it is based on polymers [10]. Because of the charge-transfer approach, the mass transport properties of OxH-based electrocatalysts have been significantly improved, which has resulted in a large rise in the electrocatalytic activity of these materials [11–15]. The following provides a detailed explanation of the EC mechanism and kinetic investigation of the OER, which results in the formation of a nickel OxHs thin film layer [16–18]. This occurs after an electrode based on nickel is being exposed to an acidic environment (Equation (1)).



It has been demonstrated that certain active electrode applications, such as those based on the transition metal OxH, have the potential to improve both OER and ORR [19,20]. Several important applications may be found for electrocatalysts that are based on metal oxides and oxygen heteroatoms (OxH) in the field of electrochemistry. These applications include energy storage, electrochemical sensor technology, and catalysis. The optical, electrical, physiochemical, and thermal properties of these substances are all distinct from one another [21]. Liang et al. [22] focused their efforts on the production of hierarchical Ni-Fe oxyhydroxide@NiFe alloy nanowire array electrocatalysts by employing a magnetic-field-assisted chemical deposition technique. Furthermore, throughout a period of 120 h, the constructed OER electrode was able to sustain current densities of 500 and 1000 mAcm⁻², respectively, when subjected to overpotentials of 248 and 258 mV. The synthesis of graphite oxide-based cobalt oxyhydroxide (GO-CoOOH) electrocatalysts by the use of gamma radiolysis is a technology that is both fascinating and scalable. An increase in the ORR electron transport rate is observed when COOH and GO come into electrostatic contact with one another [23].

In order to develop copper oxide (CuOOH) electrocatalysts, a significant amount of effort has been put forward. If, on the other hand, you wish to significantly increase the activity of OER and ORR, this electrocatalyst is your best bet [24,25]. It is responsible for producing the chemical RGO-Ni-Mn double hydroxide, which is composed of nickel and manganese. Under anodic and cathodic conditions, the RGO-Ni-Mn double-hydroxide electrocatalyst was able to achieve a current density of 37 mAcm⁻¹ for the electro-oxidation of ethylene glycol molecules at a voltage of 500 mV, surpassing the performance of Ag/AgCl. For the purpose of providing a summary of the electrocatalysts that are based on water electrolysis, OER, and HER [26–35].

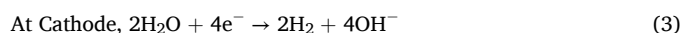
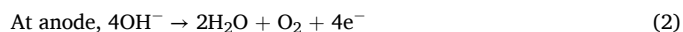
The use of photo-electrochemical cells (PEC) to split water is a potential technology for generating hydrogen fuel using solar energy. Nanostructured metal oxides have emerged as strong competitors as photoelectrodes in photocatalytic H₂ generation due to their photo-electrochemical stability, large surface area, abundance on Earth, and appropriate band gap energies. In the context of photo-electrochemical (PEC) water-splitting applications, this study discusses recent advances in the utilization of nanostructured metal oxide as photoanodes. This study's major focus is on recent breakthroughs in metal oxides, such as their synthesis methods, modification tactics, and performance in PEC water splitting. Important materials such as TiO₂, Fe₂O₃, WO₃, and BiVO₄ are thoroughly examined, with a focus on their benefits and drawbacks, as well as prospective paths for future research to increase efficiency and stability.

As a result, we decided to place a particular emphasis on the most recent study concerning OxH-based nano-composite materials, which are intended for utilization in organic electrolysis reactors, hydrogen evolution processes, and electrochemical hydrolysis. The backdrop of this article includes a discussion of water splitting as well as the OER/HER reaction. We will also briefly discuss the significant stability of electrocatalysts that are based on OxH, as well as the EC activities that

are linked with these electrocatalysts. Last but not least, this review study offers researchers access to important information that can be used in the development of intriguing new electrocatalysts that are supported by OxH and have the ability to split water and produce pure hydrogen energy. As can be seen in Fig. 1, there are a number of transition components that are mostly utilized in the manufacturing of various self-supported electrocatalysts [36].

2. Nanomaterials for water electrolysis based on oxyhydroxides (OxH)

There have been significant breakthroughs achieved in the creation of equipment that is both ecologically sustainable and economically viable for the electrochemical water-splitting process. This approach shows a great deal of promise as a feasible method for the production of clean hydrogen fuel on a large scale [37,38]. Due to the fact that hydrogen, which is a by-product of water electrolysis, does not produce any emissions, it has a great deal of promise as a sustainable fuel for the future generation of energy carriers [39]. Within the context of this particular case, the EC approach has been demonstrated to be effective for both OER and HER. To achieve a suitable reaction process, which requires the presence of overpotential, the water splitting reaction presents a substantial problem [40]. This is because the existence of overpotential is required for the reaction to be successful. The study of the alkaline electrochemical performance of OER and HER in relation to cost-effective precious metal OxH-based electrocatalysts has attracted a lot of attention [41]. During the course of the investigation into the mechanical component of the conventional electrolysis method that is utilized for the process of acidic water splitting, the following assumption was made (Equations (2) and (3)).



Electrolyzing water is a sustainable way to produce hydrogen and oxygen since water molecules are abundant. Before moving on with electrolyzer design, it is essential to have a solid grasp of the HER and OER processes, as shown in Fig. 2 [42]. The partial pressures of O₂ or H₂ are connected to the electrode potentials of the two half-reactions in Equations (4) and (5) to explain the OER and HER reaction processes.



3. The process of overall water-splitting

The overall water-splitting are following the three processes, which are given below,

- (i) These materials are semiconductive because they absorb light photons, which results in the formation of electron-hole pairs in the valence and conduction bands.
- (ii) The photo generated carriers are responsible for the separation of charges and the movement of charges. During this stage, the crystallinity, size, form, and crystal structures of the photocatalyst are all extremely important criteria to consider. Because dislocations and structural flaws have the potential to serve as recombination or trapping centers for photogenerated carriers, an effort should be made to reduce their presence.
- (iii) The surface of the photocatalyst is where the processes that require water to be broken down take place. A number of important characteristics include the surface-active sites for the cocatalyst as well as the number of active surface regions. Cocatalysts, such as platinum and ruthenium dioxide, are affixed to

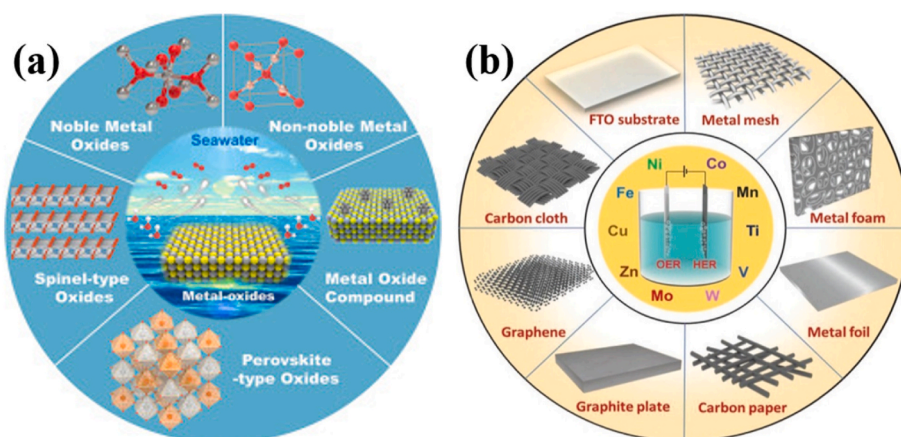


Fig. 1. (a) Transition metal-oxide based electrocatalysts for the oxygen evolution reaction for the production of hydrogen. Copyright from e-Science 2023. (b) Owing to low price and distinctive physicochemical features, the transition metal elements Fe, Co, Ni, Mn, Zn, Ti, Cu, V, Mo, and W etc. Now the most studied in the construction of self-supported transition-metal-based electrocatalysts. Copyright from Advanced Materials, 2019 [36].

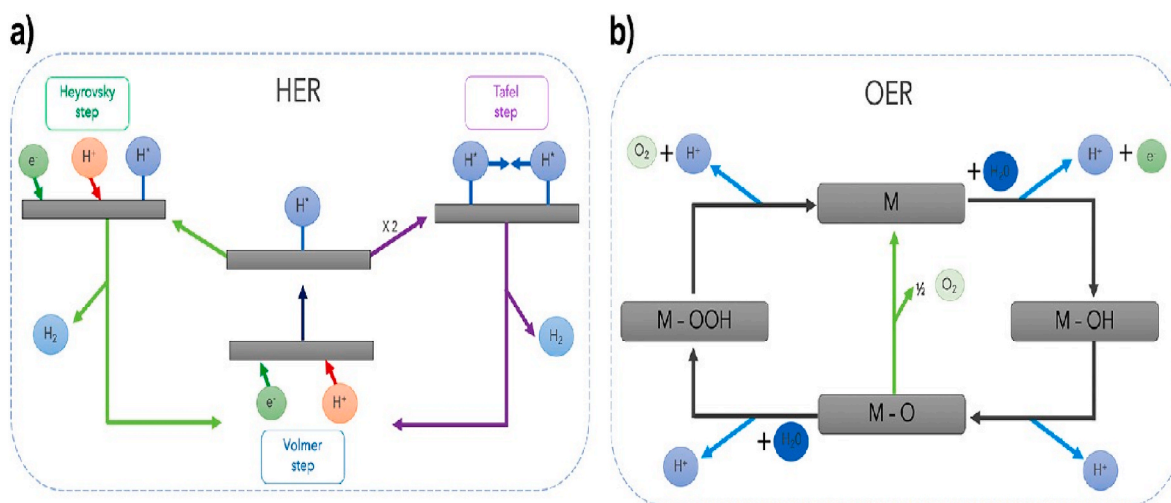


Fig. 2. (a) How hydrogen evolution on an electrode surface in acidic solutions works as a reaction. (b) How OER works in acidic environments. An M-OOH intermediate is generated as the OER continues (black line). Direct O₂ production through M-O oxo-intermediate interaction is depicted by the green line. copyright from American Chemical Society 2023 [40]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the surface of the photocatalyst in order to improve the separation of electron-hole pairs that are created by the photocatalyst. Improved photocatalytic performance can be attributed to increased active sites, which are facilitated by smaller particle sizes. The 2p orbital of oxygen is often utilized by metal oxides in order to oxidize water molecules.

Metal oxides commonly do not require a cocatalyst to undergo water oxidation. To fully dissociate 1 mol of water into hydrogen and oxygen, roughly 1.23 V is needed. At standard temperatures and pressures, the process of splitting water is thermodynamically unfavorable. Water's low ionization constant ($K_w = 1.0 \times 10^{-14}$) leads to a Gibbs free energy change (ΔG°) of 237 kJ per molecular weight, or 2.46 electron volts at the molecule level. The Gibbs free energy is calculated using the thermodynamic parameters (ΔH , ΔT , and ΔS) required for the water-splitting process [42–44]. All of these values are calculated at standard temperature and pressure. Electrodes that make use of vanadium OxHs electrocatalysts have a significant amount of promise for using water splitting activities in an efficient manner. This particular nano-sphere functions as an electrode and has a hollow centre in its innermost part. The utilization of an alkaline environment was

employed in order to achieve oxygen saturation for the purpose of conducting an investigation into the electrocatalytic activity of lepidocrocite (VOOH). According to Ref. [42], the best voltage for the VOOH electrode cell was found to be 1.62 V, and the optimal current density was found to be 10 mA cm⁻² [44]. Both of these values were proven to be optimal. At a current density of 10 mA per square centimetre, the electrode that was developed in Fig. 3, demonstrated rapid mass transfer during water-splitting and exhibited outstanding electrochemical performance. It had over-potential of 205 mV for the OER and 31 mV for the HER, respectively. Using the precipitating metal nitrate deposition (PMND) method, an electrocatalyst was created in the form of a binary transition metal hydroxide (TMOH) that possessed an amorphous nature. The water-oxidation current density of the improved Ni-Fe metal hydroxide electrocatalyst was measured to be 100 mAcm⁻², and the overvoltage was measured to be 280 mV when it was assessed under acidic circumstances. A power conversion efficiency of 13.71 % was anticipated by the research conducted on photovoltaic tandem solar cells.

In the process of designing sulphur and boron doped electrocatalysts (S,B-(CoFeCr)OOH) OxH, a reef-like ternary structure was achieved through the combination of solution combustion and wet-chemistry

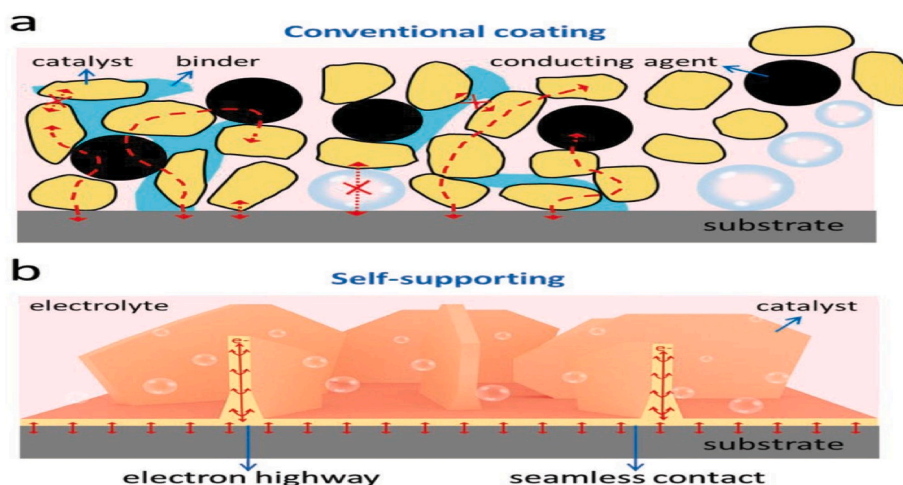


Fig. 3. Compares two kinds of catalysts, shown schematically, with respect to their electrochemical and structural properties: (a) conventional catalysts, which consist of powdered materials covered with a polymer binder and carbon additives, and (b) electrodes that are self-supported and have catalysts that are generated on-site. Advanced Materials, 2019 all rights reserved [17].

doping. Through the utilization of the oxygen that is produced, salt water can be separated in an environment that is neutral. An over-potential of 172 mV was recorded at a current density of 10 mA cm^{-2} , and a Tafel slope of 45.3 mV per centimeter was present [45]. Through the application of electro-spinning and atomic layer deposition (ALD) techniques, Zhang et al. [46] were able to successfully construct a hierarchical $\text{PrBa}_{0.5}\text{Sr}_{0.5}\text{Co}_2\text{O}_5^+$ (PBSC)/FeOOH electrocatalyst, which resulted in a material that was both highly effective and economically viable (Fig. 4-a). Additional evidence is presented in Fig. 4-b, which demonstrates that the FeOOH particles were distributed uniformly across the surface of the PBSC nanofiber to which it was exposed. In terms of the rates of the HER and the OER, the PBSC-FeOOH nanoflake electrocatalyst demonstrated remarkable electrochemical performance. According to Fig. 4-c, the current density that was expected to be present at an ideal potential was found to be 10 mA per square centimetre. While the difference between HER and OER was 280 mV, the difference

between the two was 390 mV. It is possible to credit the extraordinary performance to a number of different elements, such as the hierarchical nanostructure, the robust electrical contacts between FeOOH and PBSC, and the considerable charge-transfer capabilities. FeCo/CoFePxOy(OH) was utilized in the fabrication process of the electrodes, which produced them in a basic and cost-effective manner. For the purpose of developing a Co-Mo₂C pre-catalyst, z. Kou and colleagues [47] purposefully incorporated MoO_4^{2-} cations within a framework of Co-based zeolites. The electrodeposited bifunctional matrix that was produced as a result displayed inherent catalytic activity throughout the entirety of the water-splitting process that took place in the alkaline solution [48]. Electron transport from Mo sites to Co sites on a COOOH surface with a higher Mo concentration makes the oxidation of water easier, which may lead to an increase in oxygen bridging. Fig. 4 illustrates the outcomes of a solvo-thermal procedure that was performed in a single pot and included the ornamental FeOOH electrocatalyst Fe-doped

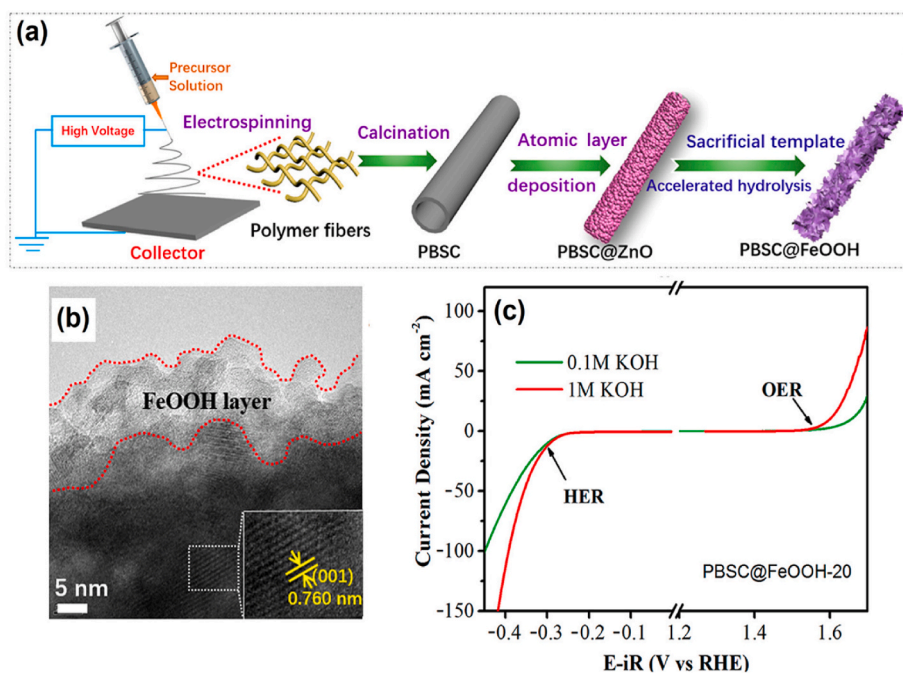


Fig. 4. (a) Core-shell structure assembly of assimilated PBSC@FeOOH-20 catalysts, (b) HR-TEM images of amorphous PBSC catalyst decorated with FeOOH, and (c) OER and HER activities of PBSC@FeOOH-20 in 0.1 M and 1 M KOH solutions. Original work by the American Chemical Society 2018 [46].

nickel-selenide on NiFe alloy foam ($\text{FeOOH@Fe-NiSe@NiFe}$). By virtue of the fact that it contains an aerophobic hierarchical hetero-structured property, the $\text{FeOOH@Fe-NiSe@NiFe}$ electrocatalyst is able to generate hydrogen through the process of water electrolysis. As a consequence of an overpotential of 224 mV at 10 $\text{mA}\cdot\text{cm}^{-2}$, the extraordinary stability and low Tafel slope of 52.67 $\text{mV}\cdot\text{dec}^{-1}$ were achieved [49].

The electrical topologies of metal oxides and hydroxides that are formed from multi-metallic elements are fascinating, and they perform exceptionally well in OER studies. For the purpose of serving as a foundation, heterostructures composed of $\text{FeVO}(\text{OH})/\text{Ni}_{0.86}\text{Mo}_{0.07}\text{W}_{0.07}(\text{OH})_2$ were applied on commercial carbon paper (CP). A high-tech technique is being utilized. Fig. 5-a and 5-b provide a schematic representation of the water splitting mechanism when it is applied in an acidic environment. In situations where higher oxidation states of metals such as Ni^{3+} , Mo^{6+} , and W^{6+} are present, the water-splitting process has the potential to reduce the ratio of Ni^{3+} to Ni^{2+} and oxidize Ni^{2+} to Ni^{3+} with more ease. The increased OER and HER activity that was observed in nano-array matrices that were based on rationally selected hybrid morphology (Fig. 5-c, d) raises the prospect that these materials might be utilized for the production of energy based on water splitting on a large scale [50].

3.1. Perspectives and challenges

Recent developments in photo-electrochemical water splitting for the production of hydrogen have shown promising progress in terms of material, structure, and catalyst development. Despite this, there are still a number of significant problems that have not been resolved in the industry. These problems include the stability of the materials, the integration of the systems (single unit and overall efficiency). Interdisciplinary techniques are the only way to handle challenges of this nature, which highlights the significance of generating practical solutions that can be implemented beyond the confines of the laboratory. In spite of the fact that the achievement of sustainable and efficient photo-electrochemical water splitting is currently in progress, researchers need to take a more critical and realistic approach in order to make progress in this promising but tough field.

An organic electrolytic reaction is one of the significant electrochemical processes that have been established in recent years. Other sustainable energy storage technologies that have been developed include water splitting, fuel cells, and batteries [51]. Some of these

technologies include water splitting. Several electrocatalysts have been utilized in the course of research on OER in environments with pH values that range from acidic to alkaline [52–54]. An O_xH electrocatalyst that is based on bimetallic compounds is an example of a type of catalyst that has remarkable EC properties during the OER process when the conditions are made acidic [55]. The OER that shown the highest level of efficiency was $\text{AMO@CeO}_2/\text{NF}$, which exhibited a positive potential of 261 mV when operating at 10 $\text{mA}\cdot\text{cm}^{-2}$ [56]. For the purpose of constructing the multilayer structure of the bimetallic-natured FeCoO_xH , we utilized the polyol approach. As a result of electrostatic attraction and electrocatalytic activity between the oxyhydroxide and the metallic core components of the $\text{Fe}_{0.25}\text{Co}_{0.75}\text{OOH}$ electrode, the overpotential for OER was found to be the lowest [57]. An electrode that has been doped with iron and NiOOH is the appropriate catalyst for alkaline organic electrolysis reactions (OERs), which are classified as organic electrolysis reactions. The catalysts with active Ni-based compounds and the Fe/NiOOH configuration displayed a remarkable improvement in OER activity [58]. The Faradaic efficiency of these catalysts was 94.5%, and they had a positive potential of 210 mV. It was determined that $\text{AMO@CeO}_2/\text{NF}$ exhibited the highest OER [56], with a positive potential of 261 mV at 10 $\text{mA}\cdot\text{cm}^{-2}$. The polyol technique was utilized in order to produce a multilayer structure that was composed of bimetallic FeCoO_xH . Because of the electrostatic connection and electrocatalytic activity of the oxyhydroxide and metallic core components, this $\text{Fe}_{0.25}\text{Co}_{0.75}\text{OOH}$ electrode is the most efficient in terms of overpotential for OER [57]. This is because of the combination of these two chemical elements. For alkaline organic electrolysis reactions (OERs), the most effective catalysts are electrodes that have been doped with iron and nickel oxide. Catalysts that utilized active Ni-based compounds and the Fe/NiOOH configuration demonstrated dramatically increased OER activity. These catalysts boasted a Faradaic efficiency of 94.5% and a positive potential of 210 mV. It is sixty. They utilized a unique electrochemical method that was devised by Hu et al. [59] in order to electrodeposit thin-film-natured transition metal (oxy) hydroxides onto nickel foam. It was only during the OER that they were able to see a transfer event that involved four electrons rather than any other. It is possible that the peroxidation process might be improved in some circumstances, and the iron substitution process could make it simpler to produce active species that are based on oxygen hydrogen. Under acidic conditions, the system exhibits a slight overpotential of 270 mV at 10 $\text{mA}\cdot\text{cm}^{-2}$ and a very modest Tafel slope of 39 $\text{mV}\cdot\text{dec}^{-1}$. This indicates

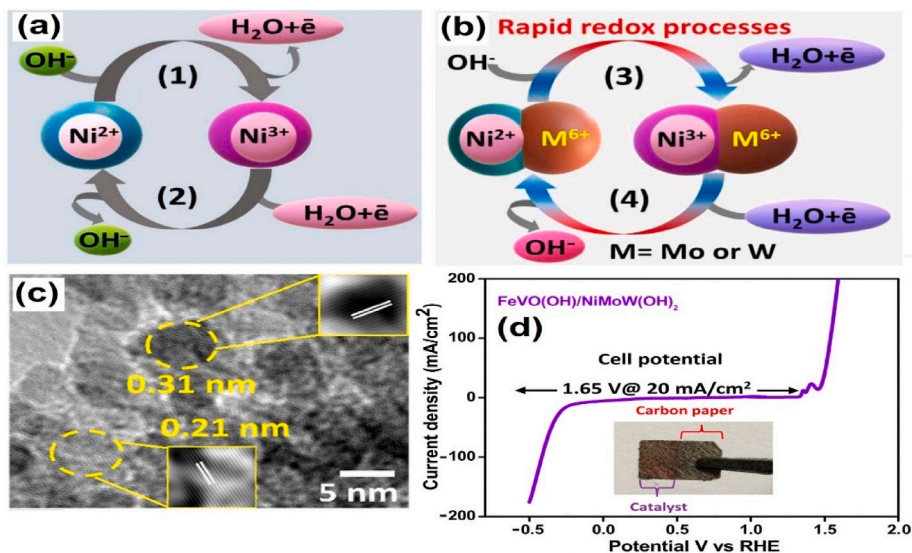


Fig. 5. The reaction process of (a) Ni(OH)_2 and (b) co-doping of Mo^{6+} and W^{6+} in Ni(OH)_2 is seen schematically in the image. The produced electrocatalyst is shown in the inset digital image of the LSV water-splitting curve of $\text{FeVO}(\text{OH})/\text{NiMoW}(\text{OH})_2$ at 1.65 V vs. RHE, and the HRTEM image of the material is shown in the second panel. In 2023, the American Chemical Society exercised its copyright [50].

that the system is able to accelerate the gradual evolution of oxygen that occurs under these conditions. As indicated by the numerical data [60]. Electrochemical research was conducted on iron oxide electrocatalysts that showed better OER. All of these investigations were conducted in depth. A low overpotential of 283 mV at 10 mV.cm^{-2} and an extraordinary intrinsic activity [61] were demonstrated by the findings for thin α -cobalt electrocatalysts that were substituted with chromium. The process of oxygen evolution additionally utilized the enhanced $\alpha\text{-Co}_3\text{CrOOH}$ electrocatalyst, which possessed a charge transfer resistance that was advantageous [62]. A nano-sword-like structure that could be compared to $\beta\text{-FeOOH}$ was created by the utilization of a straightforward and self-sustaining approach. Following the encapsulation of the structure is subsequently covered with NF, as demonstrated in Fig. 6-a. As depicted in Fig. 6-b, the FeOOH nanosword structure, which resembles a γ -like shape, exhibits a high degree of crystallinity and plays a role in the increase of OER activities.

Furthermore, in order to shed light on the electrical characteristics of the FeOOH/rGO/NF electrocatalyst that possesses a β -like structure, the LSV methodology was the approach that was utilized. Fig. 5 depicts two examples of synthesis methods, namely the electrodeposition technique and the creation of Ni(OH)_2 nanosheets and -FeOOH on nickel foam. Both of these examples are shown in the figure. In example, the oxygen evolution process (OER) of iron and nickel is accelerated by electrostatic contact, which is especially effective in an acidic environment. Using a low overpotential of 207 mV at 40 mA.cm^{-2} , the FeOOH/ Ni(OH)_2 /NF hybrid electrocatalyst demonstrated outstanding electrocatalytic activity for OER activities [63,64]. This was demonstrated by the fact that the hybrid electrocatalyst is a hybrid.

3.2. Significant remaining challenges and future perspectives

The significant challenges and future perspectives are given below

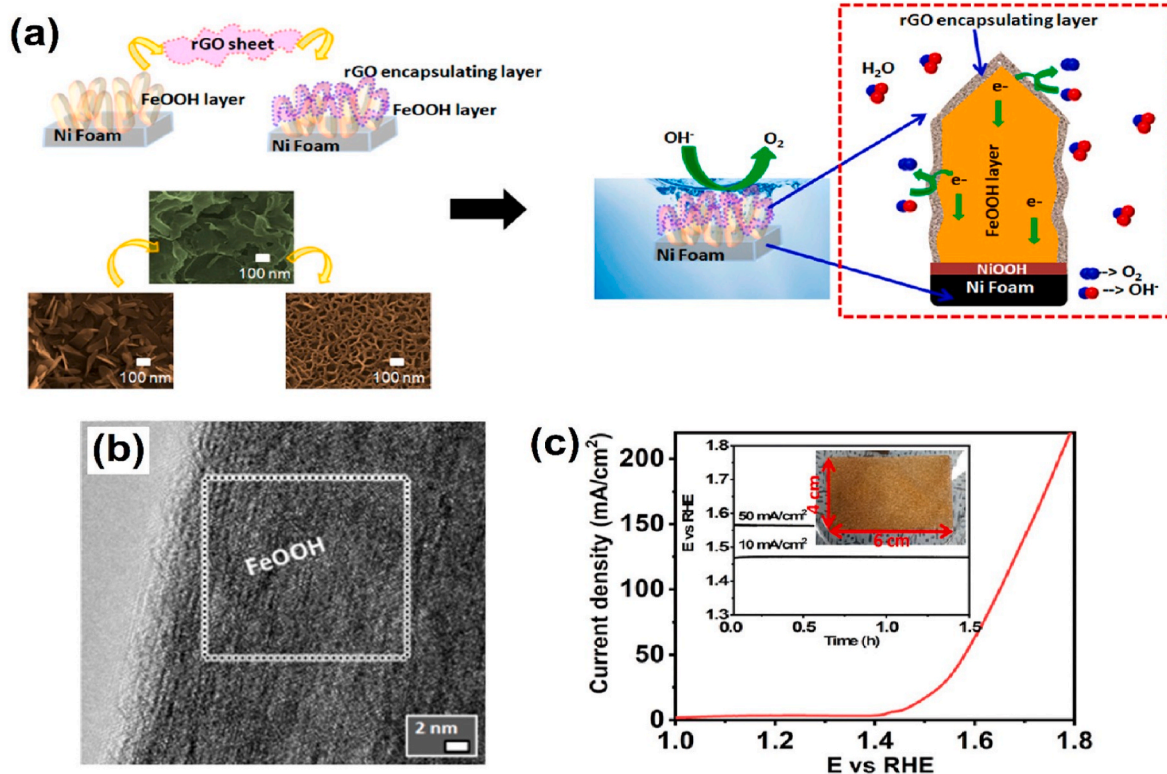


Fig. 6. (a) A β -like FeOOH was built on Ni foam and then transformed into a 3D porous structure through rGO encapsulation in order to provide oxygen evolution reaction (OER) activities. (b) A Fourier transform image of the chosen area of β -like FeOOH was taken. (c) The LSV curve of the enlarged β -like FeOOH sample, measuring 4 $\times$ 6 cm on Ni foam, was plotted. The sample's stability curve is shown in the inset photograph image. Copyright from 2021 American Chemical Society [63].

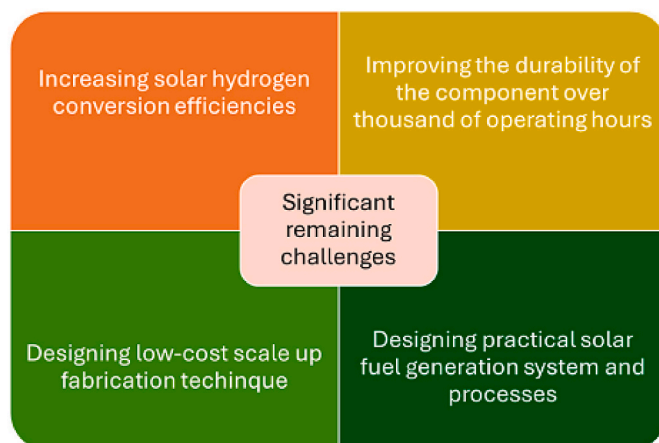


Fig. 7. Significant remaining challenges in field of water splitting methods [64] copyright from, Raub et al. Heliyon 10 (2024).

(Fig. 7), as.

- Increasing the efficiency of solar to hydrogen conversion above 10%.
- Increasing the component's resilience throughout thousands of hours of use.
- Developing low-cost fabrication methods that enable the production of the product in big quantities.
- Creating workable solar fuel generating technologies and systems.
- PEC water-splitting technology will be made more effective, stable, and cost-effective with more research on photoanode materials, interfaces, and devices based on nanostructured metal oxide materials.

4. Metal oxides catalysts

Because of their better structural and chemical structure, metal oxide-based materials have become appealing choices for accelerating the HER in recent years. Metal oxide catalysts are one of the material groups that researchers have focused on the most when it comes to the HER. These catalysts have shown outstanding HER activity and stability, which makes them desirable for use in a range of applications, such as water splitting and fuel cell technology, among others [62].

Improving the stability and selectivity of metal oxide catalysts is one of the biggest challenges in the design process for HER. Metal oxide catalysts can occasionally degrade due to a number of factors, such as catalyst poisoning, surface oxidation, and dissolution. New synthesis and surface modification strategies are now being developed to increase the stability and selectivity of metal oxide catalysts for HER. These efforts are currently underway. Materials for the HER system, which have the potential to significantly facilitate the broad adoption of hydrogen-based technologies for the production and storage of clean energy. Materials known as electrocatalysts are those that reduce the amount of activation energy that is necessary for electrochemical processes to take place. Electrocatalysts are responsible for the conversion of protons and electrons into hydrogen gas within the framework of the HER. It is essential to carry out this process in order to enhance the effectiveness, selectivity, and stability of the HER and to make it possible for hydrogen-based technologies like fuel cells and water splitting to be put into practice [65,66].

Transition metals, carbon-based materials, and metal chalcogenides are examples of electrocatalysts that are frequently investigated for the HER. Additionally, the operating parameters of the electrochemical cell are taken into consideration when evaluating the performance of electrocatalysts. These criteria include the chemical composition, crystal structure, morphology, and surface area of the electrocatalyst. In order to improve the HER process and optimize electro-catalysts for the production and storage of clean energy, research investigations are now being carried out.

4.1. Advantages and disadvantages of HER

Achieving the widespread deployment of hydrogen as a clean energy carrier would require HER catalysts that are both economical and efficient. The main focus of this field's research and development is on creating new catalyst materials and improving their activity, stability, and selectivity. However, the widespread use of technologies that would increase productivity, lower costs, and limit the environmental impact of the processes involved would require the development of cost-effective HER catalysts. Among other hydrogen-based technologies, the HER is a groundbreaking procedure. Among the most prominent technologies based on hydrogen energy are hydrogen fuel cells, hydrogen synthesis via water electrolysis, photo-electrochemical water splitting, and hydrogen storage [21]. Through an electrochemical reaction, the hydrogen energy converter in fuel cells is responsible for converting the chemical energy of hydrogen gas into electrical energy. An electric current is used in water electrolysis, which results in the production of hydrogen gas from renewable energy sources. On the other hand, photoelectrochemical water splitting uses sun energy to power water electrolysis and generate hydrogen gas. Although solid-state materials such as metal hydrides or carbon-based compounds can also be used, compressed gas or liquid form can be used to store hydrogen. Under some conditions, the HER is also involved in the storage of hydrogen. One instance of this is when hydrogen must be released by a reaction with water that occurs in the presence of a catalyst because it is held as a metal hydride.

HER is a possible source of renewable energy that offers a number of benefits to interested parties. The fact that hydrogen gas is a clean energy source, with the sole consequence being water vapor, is one of the most significant advantages of this substance. Because of this, it is a

potentially useful strategy for lowering carbon emissions and addressing the issue of climate change. In addition, hydrogen gas possesses a high energy density, which makes it a potential candidate for use as a fuel in applications related to transportation (Fig. 8).

The fact that the HER may be powered by available resources, such as water, biomass, and waste products, is still another advantage of the device. Because of this, it is a potentially useful alternative for lessening reliance on fossil fuels and fostering a more sustainable energy future. In addition, the HER is appropriate for a wide variety of commercial and industrial applications due to its scalability, which allows it to be utilized for everything from the creation of hydrogen on a small scale to the generation of power on a big one. Due to the fact that hydrogen gas can be utilized as a fuel for fuel cells or for chemical synthesis in a variety of industrial processes, the adaptability of the HER is another significant advantage. Nevertheless, the HER is also associated with a variety of difficulties that must be overcome. The high expense of the catalysts that are used to fuel the reaction is one of the most significant challenges. The reaction has a low efficiency, particularly in terms of current densities, which is another problem that must be overcome. Furthermore, the kinetics of the reaction might be slow, particularly in alkaline solutions, which can restrict the practical applications of the reaction. The hydrogen generation, storage, and transportation of hydrogen gas are all examples of infrastructure difficulties that are related with the HER. Additionally, it is necessary to solve safety concerns that are associated with the immobility and explosiveness of hydrogen gas. Finally, there are environmental problems that are related with the production of hydrogen gas from fossil fuels. This occurs because the manufacturing of hydrogen gas can contribute to emissions of greenhouse gases as well as other environmental repercussions. However, in order to overcome these obstacles and make it possible for general use, the HER will require constant research and development. This is despite the fact that it has significant potential as a source of clean energy.

4.2. Transition metal hydroxides/oxyhydroxides

A significant amount of research has been conducted on electrochemical catalysts (Fig. 9a) that make use of stacked double hydroxides, particularly for OER [68]. It is possible to easily program the composition and structure of LDHs in order to produce a self-supporting electrode. This can be accomplished by altering positively charged layers or interlayer anions. For the purpose of supporting amorphous meso-porous NiFe hydroxide sheets on NF substrate, a basic, one-step electrodeposition method was utilized [69]. This method was utilized by using the NiFe LDH as an example, which has been investigated the most thoroughly. With a current density of 200 mAcm² at an overpotential of 240 mV and a time of flight (TOF) of 0.075 s¹ at an overpotential of 400 mV, the synthesized electrode was able to achieve a current density that was three times faster than the Ir/C electrode, which had a rate of 0.027 s¹. It has proven possible to greatly improve the electrocatalytic performance of LDH materials through the creation of nanocomposite materials or through the application of cation doping. An uneven coating of Ni-Fe hydroxide was generated on top of the Ni₃S₂ nanosheets as a result of the formation of the Ni-Fe-OH@Ni₃S₂ compound, as shown in Fig. 9b. The fast synthesis of amorphous Ni-Fe bimetallic hydroxide films on NF-supported Ni₃S₂ nanosheet arrays is one of the recent discoveries that have been made by Zou's group. The monitoring of the reaction between Ni₃S₂ and Fe³⁺ in an aqueous solution was the method that was utilized to accomplish this goal (Fig. 9c) [70]. The self-supported Ni-Fe-OH@Ni₃S₂/NF electrode has an exceptional and stable OER activity (165 mV overpotential at 10 mAcm²). This is a result of the electrode's advantageous structural properties. A highly linked interface, the high intrinsic activity of amorphous Ni-Fe hydroxide, and the high conductivity of a Ni₃S₂ array are some of the properties that are included in this category. In addition, NF was utilized in the process of cultivating V-doped Ni-Fe LDH nanosheets arrays. According to the findings of an electrochemical investigation and a

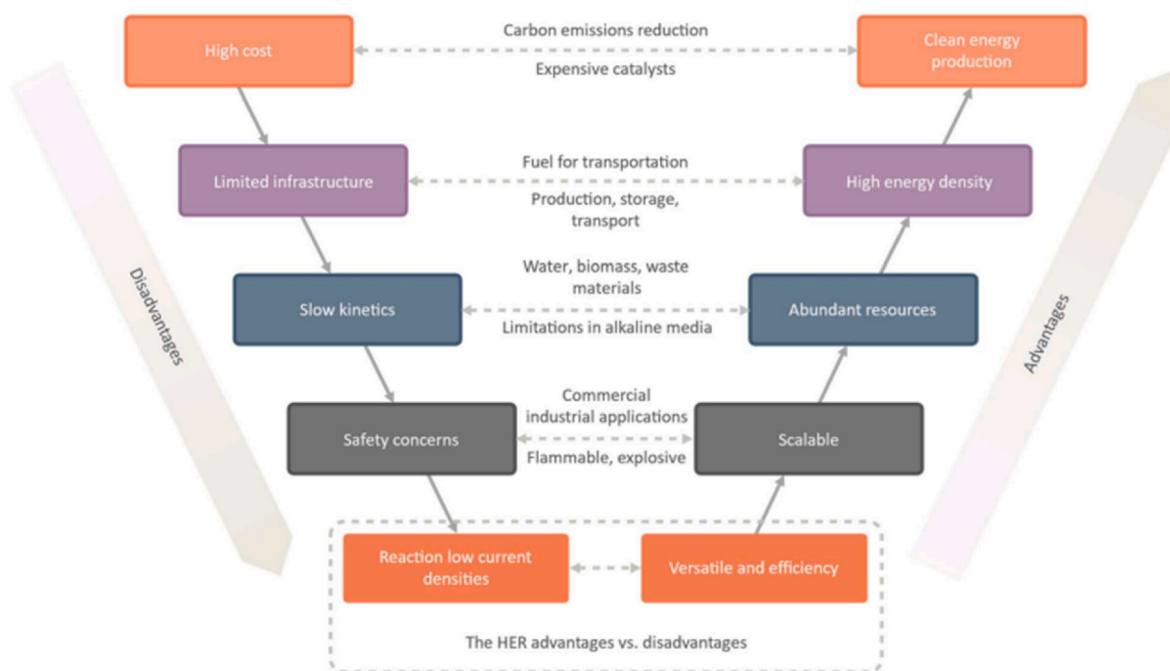


Figure 8. Comprehensive exploration of advantages and disadvantages of the HER. Copyright from RSC Sustain, 2023 [67].

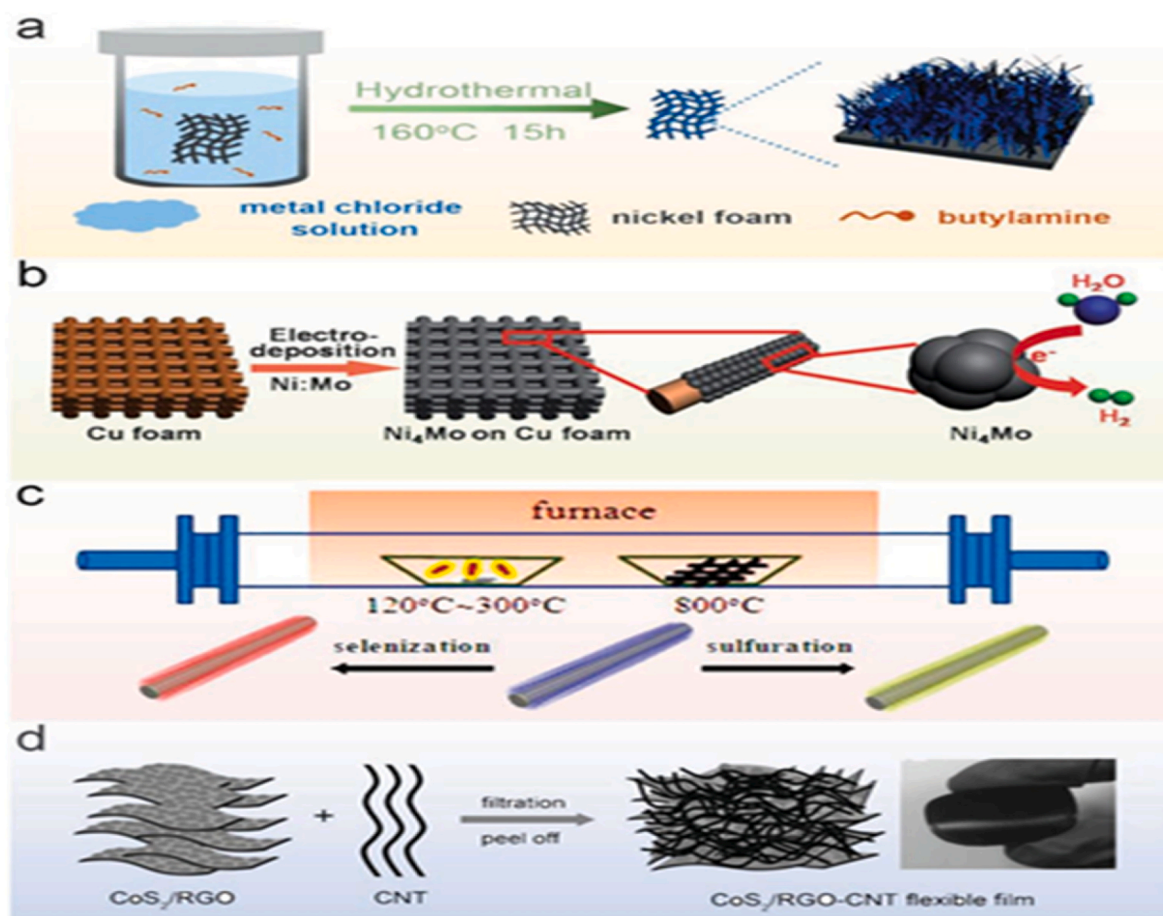


Fig. 9. Typical synthetic approach for self-supported electrodes. (a) Oxyhydroxides on nickel foam undergo hydrothermal development. (b) Ni–Mo electrocatalysts deposited onto Cu foam by electrodeposition [68]. (c) WS_2 , WSe_2 , and $\text{WS}_{2(1-x)}\text{Se}_{2x}$ are grown on carbon fibre by chemical vapor deposition. (d) A method in which decreased graphene oxide-carbon nanotubes and cobalt sulfide nanocomposite are obtained by filtration and peeling off [65,66,68].

density-functional theory (DFT) calculation, vanadium doping made a significant contribution to the enhancement of OER activity. This was accomplished by modifying the electrical structure and decreasing the bandgap. Co–Zn nanosheets/zinc foils, Ni–Co LDH nanosheets/carbon paper, and Co–Al LDH nanosheets/3D graphene network are some examples of other transition metal hydroxide-based self-supported OER catalysts that have been demonstrated (Fig. 9d). These catalysts are in addition to the Ni–Fe bimetal family.

Due to low catalyst loading and poor adhesion on the current collector, most reported LDHs demonstrate significant gravimetric activity, but they often cannot afford large current density and long-term stability. We have recently created a flexible and readily scalable method for the electro-synthesis of metal hydroxides and oxides on graphitic substrates in order to solve this problem. The cathodic reduction of nitrate ions produces OH, which is then converted to metal hydroxide,

4.3. Why metal oxide nanomaterial and nanotechnology?

A large amount of interest has been generated in metal oxide nanomaterials and nanotechnology as a result of the distinctive features that they possess at the nanoscale. A high surface area, a band gap that can be tuned, increased catalytic activity, and improved electrical, optical, and mechanical performance are some of the qualities that are contained inside this material. As a result, metal oxide nanoparticles and nanotechnology have a wide range of applications in a variety of sectors, including the domains of energy, the environment, healthcare, and electronics [68]. In order to enhance the performance of solar cells, supercapacitors, and batteries, for example, metal oxide nanoparticles are utilized. This makes it possible to produce and store energy in a manner that is both more efficient and more environmentally friendly. They have also been used in environmental applications such as pollution degradation, air filtration, and water purification, all of which have improved the quality of water and air resources. Among other things, they have made advances to the fields of medication delivery, diagnostics, and regenerative medicine. All things considered, metal oxide nanoparticles and nanotechnology have a great deal of promise for addressing some of the most important issues facing the world today and promoting sustainable development. A brief overview of the important role metal oxide nanoparticles play in applications related to environmentally friendly and sustainable energy is provided below: Improved characteristics of metal oxide nanoparticles include a large surface area, a tunable bandgap, and improved catalytic activity. These properties make them ideal for a variety of applications in the fields of energy and the environment. Metal oxide nanoparticles may improve the efficiency of energy storage systems like supercapacitors and batteries. The capacity, rate capability, and cycling stability of these devices can all be enhanced by these nanomaterials, which is crucial for the integration of electric vehicles with renewable energy sources. Metal oxide nanomaterials have the potential to be very efficient photo-catalysts in the photocatalytic water splitting process, producing hydrogen as a clean and renewable energy source. Metal oxide nanoparticles can be used as light-absorbing or electron-transporting layers in solar cells to increase the stability and efficiency of the cells.

5. Materials for HER based-on transition metal oxygen

In the drive to deliver inexpensive, clean energy, hydrogen protection has emerged as a key player because to its efficiency and natural eco-friendliness. So far, researchers have studied the HER in electrolysis under alkaline circumstances using heterostructure active electrocatalysts based on O_xH -based electrode materials. A two-electron transfer is shown by this reaction (Equation (6)) [66].



The HER and the OER are the two primary half-reactions that occur during the electrolysis of water and ultimately result in the production of hydrogen. On nickel foam, a three-dimensional (3D) hierarchical structure of iron O_xH -supported Ni_3S_2 was created. This structure is not only innovative but also strong and efficient. The electrocatalyst that was constructed out of FeOOH and Ni_3S_2/NF was able to efficiently enhance the reactions of OER and HER. According to the reference, the over-potential for HER was 94 mV when the current was $10 \text{ mA} \cdot \text{cm}^{-2}$, and the over-potential for OER was 280 mV when the current was $50 \text{ mA} \cdot \text{cm}^{-2}$. Ni-foam was used as the basis for the porous nickel electrocatalyst that the researchers developed in order to enhance their HER and OER activities. This substance has a heterogeneous interaction with FeOOH, which results in the production of a greater number of oxygen vacancies and a faster electron transfer process [71]. The utilization of heterogeneous nature type crystalline (cNiFe) or amorphous-based bimetallic (NiFe) NiMo substrates for the production of oxide hole heaters (O_xH s) is a significant method for controlling the electrodeposition process. A remarkable electrocatalytic activity was demonstrated by the bifunctional-natured NM@NF/NFO that was synthesized in the HER, OER, and entire water-splitting methods [72]. Additionally, *in situ* vertical growth was utilized in order to fabricate $Ni(OH)_2$ nanosheets on NF. The transformation of these nanosheets can be accomplished through a two-step HT process by utilizing NiFe-LDHs, which are double-layered hydroxides with a bimetallic character. Electrocatalysts composed of bifunctional NF– $Ni(OH)_2$ –NiFe-LDHs were able to make it possible to achieve a low overpotential of 116 mV at $10 \text{ mA} \cdot \text{cm}^{-2}$ during the HER process [69]. Overpotential of this magnitude was achieved. In Ref. [70], an easy and regulated approach for surface restoration was described. This process involved the utilization of ZnCo phosphate and (oxy) hydroxide that was abundant in Co^{2+} or Co^{3+} . In addition, the reconstructed electrocatalyst was able to continuously improve the performance of the HER when it was subjected to alkaline electrolytic conditions. After conducting an examination of the performance of the HER using density functional theory (DFT), we have determined that the electrocatalyst that was created has a significant potential for application in the degradation of industrial effluent. This was accomplished by adopting a conventional HT and phosphorization method on a carbon red (CR) substrate, which resulted in the creation of a CoMn hydroxide nanowire comprised of defect-rich active sites. Using Mn–CoP, a nanowire has been successfully manufactured. In order to successfully meet both the HER and the OER, a combination of Mn–CoP nanowires and MnCoOOH was utilized [73,74] conducted research on three nickel selenide compounds: $Ni_{0.85}Se$, $NiSe_4$, and $NiSe_2$. This research is extremely important. The stoichiometric ranges of these chemicals are not consistent. NiOOH has the potential to govern the kinetic current and influence the HER and OER performance of nickel selenide, which is an intriguing fact to take into consideration. The electrode for three-dimensional (3D) porous-network-based Fe@Ni nanofibers is shown in Fig. 10a. This electrode is the end result of the chemical reduction method that was reported by Tao et al. [75]. According to the findings of the electrode investigation, the surface of the Ni/Fe (oxy) hydroxide electrolyte contains a high concentration of active sites because of its composition. Using scanning electron microscopy (SEM), the surface morphology was investigated, and it was discovered that the diameter of the Fe@Ni nanofibers was approximately 200 nm. It was necessary for the active Fe@Ni nanofiber electrocatalyst to have a low overpotential of 55.0 mV for HER and 230.0 mV for OER in order to achieve a current density of $10 \text{ mA} \cdot \text{cm}^{-2}$, as shown in Fig. 10b. The application of arrays of bifunctional-natured $FeCo_2S_4$ nanosheets to 3D nickel foam (NF) is depicted in Fig. 11-a. These nanosheets were synthesized by Hu et al. [76] by a basic HT method. The electrocatalytic layer of the Co(Fe) oxyhydroxide active species has been independently validated by the utilization of XPS research. As can be seen in Fig. 10c, the $FeCo_2S_4/NF$ electrode, in its current state, demonstrated remarkable activity in relation to the HER, as well as the consistent maintenance of its electrocatalytic activity over an extended period of time for the

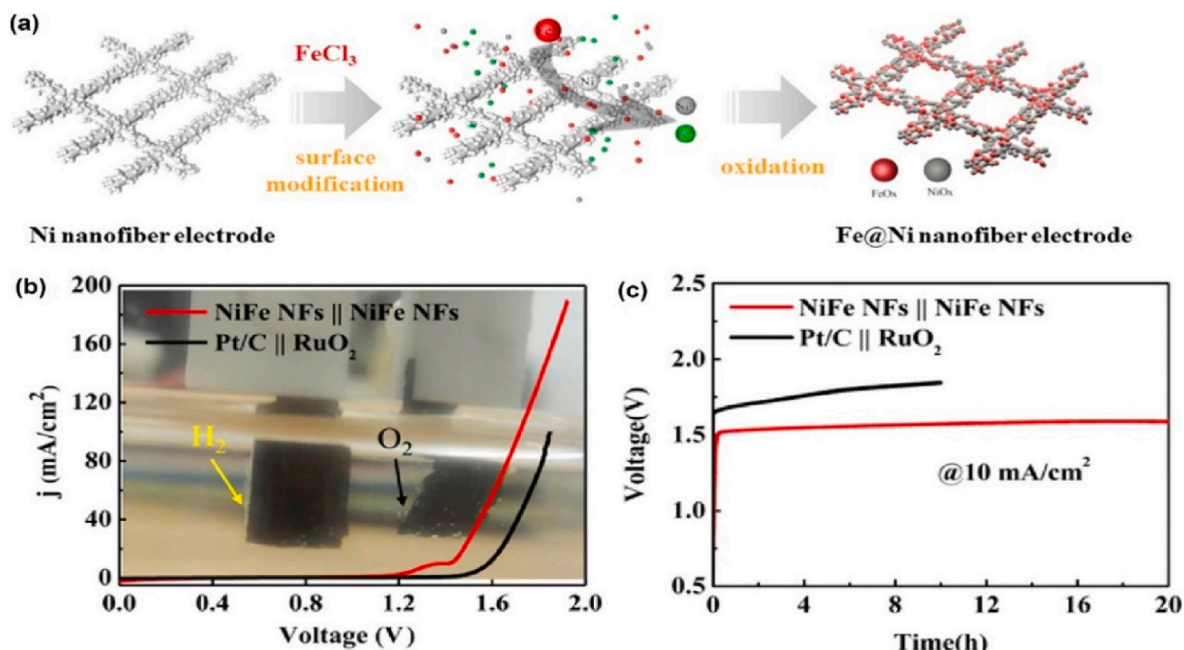


Fig. 10. (a) A diagram showing the process of surface modification on the Fe@Ni nanofiber electrode; (b) The experimental results of the electrochemical characterization of the Fe@Ni nanofiber electrode and the Pt/C||RuO₂ coupling in the water-splitting reaction as a whole; and (c) the stability test of the electrode at a current density of 10 mA·cm⁻². American Chemical Society holds the copyright for 2019 [75].

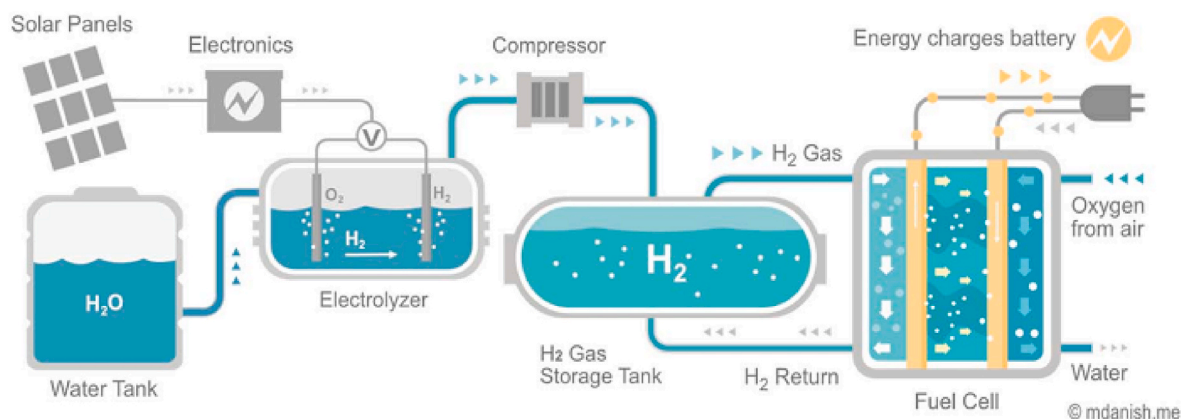


Fig. 11. The A typical green hydrogen fuel cell representation. Copyright from RSC, Sustainability, 2023 [67]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

purpose of water splitting in acidic conditions.

6. Optically excited and highly efficient transition metal-oxides

The future of hydrogen-producing systems that make use of renewable energy sources (Fig. 11), such as EC water splitting, is something that needs to be continuously monitored. For the water-splitting OER and HER processes, dependable catalysts are required in order to reduce the accumulation of over-potentials and guarantee that the movement is carried out correctly [77,78].

The most sophisticated electrocatalysts for the OER in both acidic and alkaline circumstances are precious metal oxides. Examples of such oxides include iridium dioxide (IrO₂) and ruthenium dioxide (RuO₂). It is possible that the greater anodic potentials of these compounds are the cause of their instability in electrolytes and their subsequent breakdown into IrO₃ and RuO₄ when they are dissolved in water [79]. Because of their excessive prices, precious metal oxides, which are both uncommon and expensive, are only occasionally used in production. This is because

of their scarceness. Because of the potential applications that they offer in energy storage and conversion, transition metal oxides including nickel (Ni), iron (Fe), cobalt (Co), and manganese (Mn), amongst others, have attracted a lot of attention in recent years [80].

The use of nickel and nickel alloy electrodes as components of alkaline medium batteries and supercapacitors has been shown to have substantial promise [81]. Nickel is a transition metal, which means that it belongs to that group of metals. In the context of alkaline OERs or HERs, electrocatalysts that consist of a mixture of metal oxides and a variety of functional additives have been largely considered to be the most effective (Fig. 12).

A number of desired characteristics are possessed by these catalysts, including mass transfer, conductivity, structural recital stability, and synergistic action between mixed metal oxide and OxH. The electrocatalyst that was developed by Babar et al. [34] displays the capability to wet-chemically deposit FeOOH nanoparticles (CoFe–OH@FeOOH) and to enable the splitting of water. Utilizing nickel foam substrates and two-dimensional cobalt-iron hydroxide nanosheets allowed for the

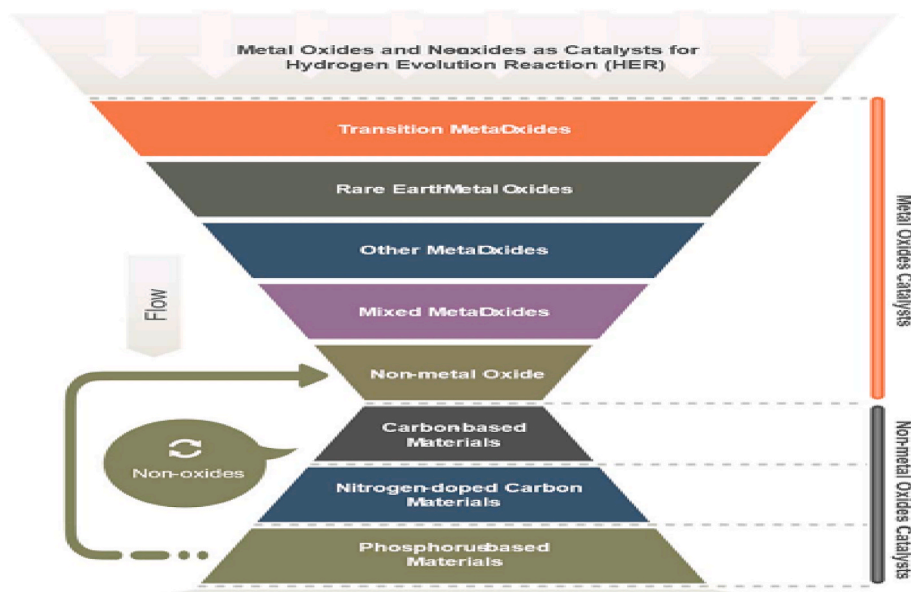


Fig. 12. Various types of metal oxides for HER mechanism. Copyright from RSC Sustain, 2023 [67].

successful completion of this task. Because it had a large surface area and a number of active sites, the nanocomposite was able to display rapid water separation in electrochemical cells. With a current density of 50 mAcm^{-2} , the electrode displayed an over-potential rate of 200 mV, which was a significantly lower value than expected. As a result of its low cell voltage of 1.56 V and current density of 10 mAcm^{-2} , it was able to perform the functions of both the anode and the cathode in a process that involved the entire splitting of water. Because of the synergistic effect of the interface between CoFe-OH and FeOOH , there were significant improvements in both the conductivity and the mass transport of the material. It is possible that this basic technique will give an alternative viewpoint regarding the development of efficient electrodes for applications involving energy conversion as well.

An innovative oxygen-reduction deposition method was developed by Yan et al. [82] for the purpose of producing Ni-incorporated FeOOH nanosheets in an acidic environment. The over-potential that was measured at 239 mV at a current density of 10 mAcm^{-2} , in conjunction with a moderate Tafel slope of 33 mVdec^{-1} , provides evidence that the

OER activity that was measured must be taken into consideration. This method stands out due to the fact that it has extremely low synthetic expenses, meaning that it does not require high temperature or pressure or noble materials. Additionally, the synthetic time for this method is rather short, taking roughly 20 min. This discovery has the potential to build a fundamental basis for exploring nano electrocatalysts that make use of FeOOH and are both highly efficient and cost-effective. The process of producing Ni- FeOOH nanosheets is depicted in Fig. 13, which shows the procedure. The intrinsic redox potential difference between the Fe substrate and the dissolved oxygen is the driving force behind the manufacturing process. It was found that the presence of seven percent nickel heteroatoms on surfaces led to an increase in the number of electron acceptors, a decrease in the Fermi level, and an increase in the average valence of iron that was greater than three times that of nitrogen. By comparing pure FeOOH to the energy barrier of the rate-determining phase for Ni and Fe sites, it is possible to explain the observed increase in OER activity in an acidic environment. This is because the energy barrier is lower for Ni and Fe sites.

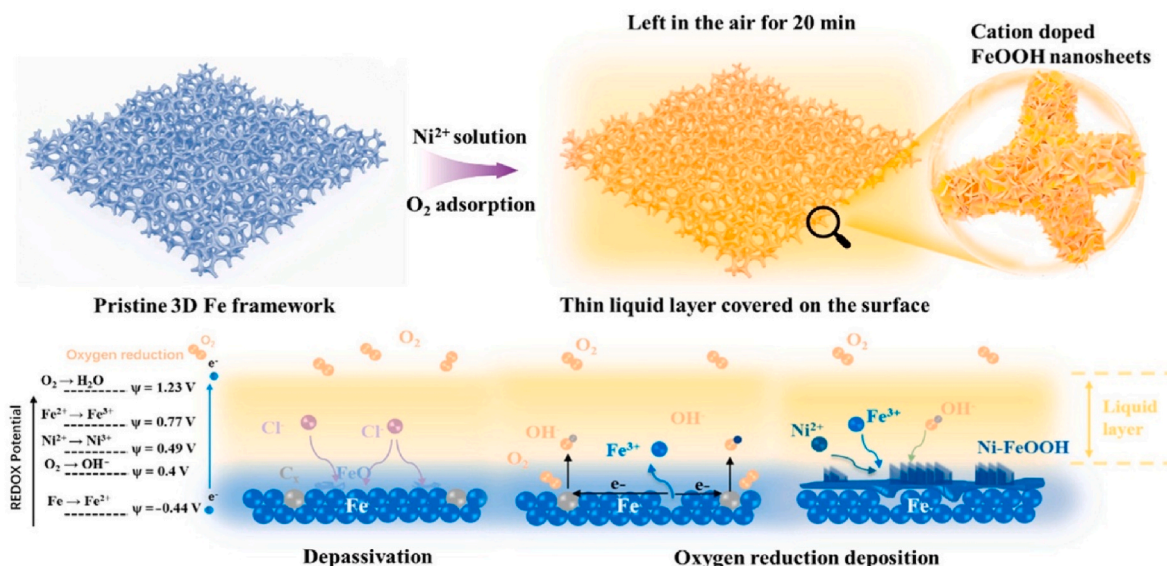


Fig. 13. Schematic representation of Fe-NiOOH nanosheets production through method of oxygen reduction deposition. Copyright from the Elsevier [82].

Researchers Ge et al. [83] used a one-step chronoamperometry electrodeposition technique to perform a study on a bifunctional $\text{NiFeMn}_{\text{alloy}}/\text{NiFeMnO}_x\text{H}$ electrocatalyst that was both highly successful and cost-effective. Fig. 14 illustrates the results of their investigation. Calculations using density functional theory (DFT) showed that the energy barrier for the OER and HER was significantly reduced when Mn was doped into a multilayer dendritic NiFeMn alloy, which led to the addition of an OxH layer. At a current density of $10 \text{ mA}\cdot\text{cm}^{-2}$, the newly designed catalyst demonstrated remarkable electrocatalytic activity for the OER at 219.0 mV and the HER at 19.0 mV. Both of these reactions were considered successful. Exciting new opportunities in the realm of industrialization have been made available as a result of the remarkable theoretical and actual performance of this catalyst for full water splitting.

6.1. Roles of metal oxide (MOx) nanoparticles in biomedical applications

This article provides a summary of the numerous methods that can be used to synthesize MONPs, including ZnO , Fe_2O_3 , CeO_2 , TiO_2 , MgO , NiO , ZrO , and CdO NPs. Other types of nanoparticles can have their performance and applications improved with the application of further modifications, despite the fact that some of these nanoparticles already exhibit some biological effects in their raw nanoparticles form. These modifications entail the surface functionalization of nanoparticles (NPs) in such a way that they are able to elicit more specific responses, which may be more advantageous from a chemical or biological standpoint. It is important to note that the majority of the synthesis procedures produce hydrophobic NPs. This is because the circumstances of the synthesis process and the utilization of surfactants both contribute to the formation of these NPs. The NPs' ability to dissolve in aqueous or biological environments is consequently hindered as a result of this. Surface modifications can be accomplished by a variety of methods, some of which include functionalization with medicines, polymers, biopolymers, inorganic compounds, or bio conjugation in Fig. 15. Techniques that can be used to achieve this include coating, conjugation schemes, *in situ* synthesis, self-assembly, surface encapsulation, and the production of core-shell nanoparticles. The functionalized nanoparticle is compatible with the biological environment after the surface modification is finished. The hydrophilic nature of the coated shell in connection with drug functionalization is primarily responsible for this. There are two main advantages to using MONPs. The first is related to the potential for localizing the medication to the target cell or region, which greatly boosts the drug's potency while also lowering the dosage and, consequently, removing the concern of tissue toxicity. Secondly, the presence of a surface coating (shell) on the MONPs has the potential to stabilize the nanoparticles, influence the size of the colloid particle, as well as their bio-kinetics and distribution inside the body, and reduce the toxicity of the nanoparticles [167]. An extensive assortment of specific

medications, including anticancer, anticonvulsants, immune-suppressants, antibiotics, anti-inflammatory, antiviral, antifungal, or alternative medications, may be utilized in the treatment of the patient. In order for loading and release kinetics to be dictated by affinity to binding substrates and localized environments, the pharmaceuticals can either be covalently bound to the surface of the MONPs, or they can be bound via electrostatic interactions, or they can be functionalized sequentially.

The production of nickel/nickel (oxy)hydroxide hybrid films was made possible by Ref. [85] by the utilization of a novel method that involves the manipulation of oxygen deficits at the surface of the catalyst. The overall catalytic performance for water splitting was significantly improved as a result of the application of these films. In Ni(II) films that have been produced in an ethylene-based deep eutectic solvent (DES) under OER conditions, a phase shift takes place during the process of surface and structural rearrangement. The intrinsic activity of the catalyst is increased, which results in structural disordering and a significant improvement in the efficiency with which it splits water. The addition of nitrate ions, on the other hand, results in the formation of an imperfect precursor, which in turn leads to a rise in oxygen deficits. In accordance with the information presented in Ref. [86], solvothermal Ni@Fe-NP electrocatalysts demonstrate great efficacy, extended durability, and environmental compliance. The development of amorphous Ni@Fe-NP is illustrated in Fig. 15. The oxygen electrode that was produced not too long ago possesses outstanding electrocatalytic characteristics in the process of oxidizing acidic water. It also displays durability under prolonged conditions, demonstrating an overpotential of just 211 mVs at a current density of 10 mAs per square centimetre. An extremely acidic solution was used to test the oxygen evolution electrode, which was first developed as an amorphous Ni@Fe-NP rippling nanostructured electrode. The electrode demonstrated outstanding performance overall. Because of the findings of this research, there is a possibility that additional research might be conducted on self-sustaining electrodes. These electrodes could be useful in the field of water splitting and other related domains. Through the use of the electro-spinning process, Poudel and Kim were able to successfully design a hierarchical nano-catalyst. This was accomplished by depositing hematite-iron oxide onto hollow porous carbon nanofibers and ternary Zn-Mg-Al -based double-hydroxide nanosheets. It has been demonstrated through capacitance measurements that were carried out at a current density of 1.0 mAcm^{-2} that the $\text{Zn}\%$ has an effect on the electrochemical, structural, and morphological properties of the 1D-hollow/2D-mesoporous/3D-bimetallic nanocomposite. Using hierarchical CoMoP nanosheets that were wrapped around Ni_3S_2 nanowires and directly placed on nickel foam, Yoo et al. were able to successfully achieve both the OER and the HER. A significant decrease in the 6.8 mV overpotential of alkaline HERs was seen as a consequence of the utilization of the catalyst that was recommended. This occurred when the

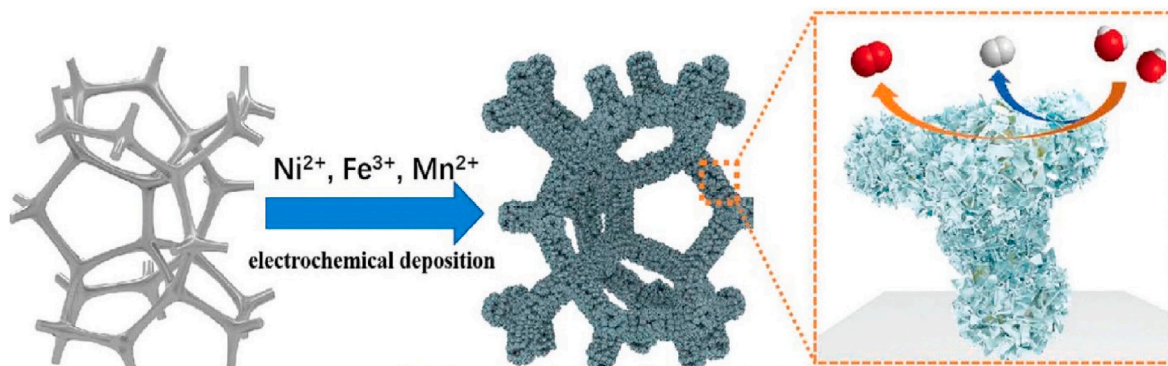


Fig. 14. A schematic showing the fabrication process of a Ni–Fe–Mn-AOs electrode and its catalytic function for OER and HER. Copyright by the Royal Society of Chemistry 2021, [83].

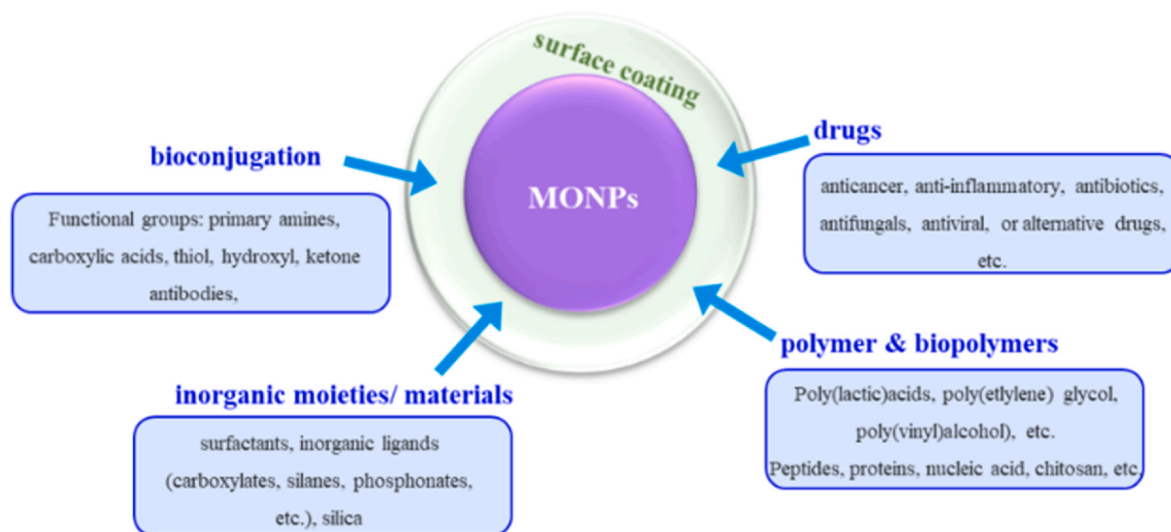


Figure: 15. Overview of the different surface modification/functionalization of MONPs usually applied for improving the biological effects [84]. Copyright from the J. Funct. Biomater. 2022, 13, 274.

reactions were producing hydrogen intermediates. The catalyst did not show any evidence of deterioration even after being subjected to thirty cycles in an acidic environment [1,2].

6.2. Biological effects pro-regenerative potential

Within the realm of biomedical research, nanotechnology has presented a multitude of potential techniques over the course of the past few years. These approaches aim to accelerate the transfer of regenerative medicine from the research stage to the clinical practice stage. One of the many types of materials that are utilized in nanotechnology is NPs, particularly metal-organic nanoparticles (MONPs). These nanoparticles are a class of materials that are extensively distributed and feature distinctive physical and chemical properties. They have various advantages and multiple applications in the fields of biology and biomedicine (Fig. 16). Within the realm of wound healing is one such use. Wounds that are superficial or deep can be caused by trauma, unique skin disorders, burns, or the loss of the skin as a result of surgical treatments. These wounds can be susceptible to pathogenic colonization

and subsequent complications if they are not covered and managed effectively. In this particular scenario, it is essential to have wound dressing materials that are acceptable, include antimicrobial qualities, and have the capacity to encourage healing [84].

7. Metal oxychloride for use in OER and HER

Metal oxides that have been doped with rare-earth metals exhibit remarkable characteristics as a result of the enhanced surface area, conductivity, and diffusion pathways that are brought about by the dopants. A few of the obvious benefits that particular metals and metal oxides offer include enhanced catalytic activity, carrier transportability, and ionic conductivity. These are only a few of the more notable advantages. The emergence of abundant rare-earth electrocatalysts for OERs and HERs in strong acids presents a significant challenge to the development of electrolyzers and fuel cells that are both environmentally friendly and economically viable [87,88]. The rare-earth Dy-doped cupric oxide nanoparticles ($\text{Cu}_x\text{Dy}_x\text{O}$) electrocatalysts were able to reach the standard current density of 10 mAcm^{-2} in an aqueous 1.0 M KOH

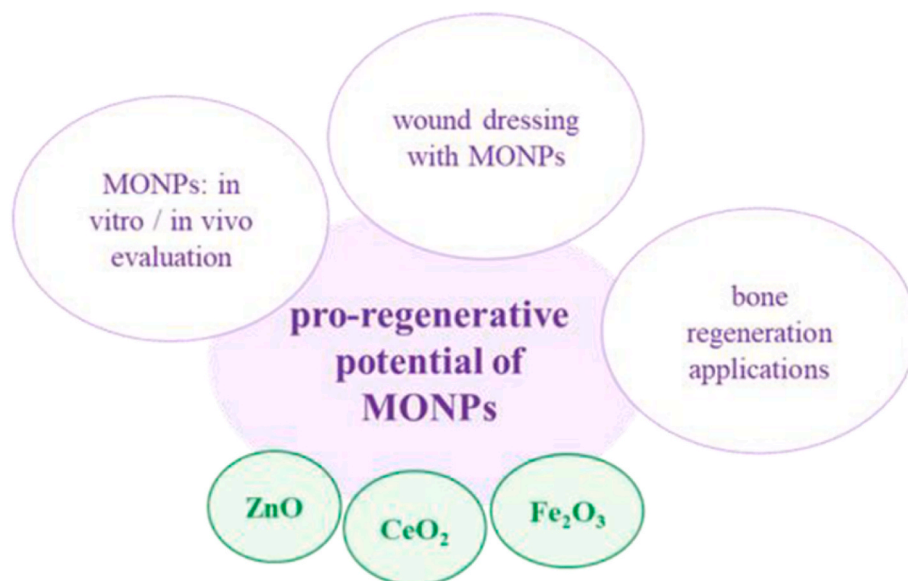


Fig. 16. MONPs and their potential for pro-regenerative properties [84]. Copyright from the J. Funct. Biomater. 2022, 13, 274.

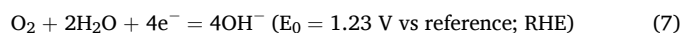
electrolyte. This was made possible by their high selectivity (HER) and outstanding open electrode potential (OER) of 0.036 V vs RHE [89]. The synthesis of NiFe-LFO involved the use of the solvothermal technique, which was followed by calcination at a variety of temperatures. To create NiFe-LFO samples with different Ni concentrations and $\text{Fe}^{3+}/\text{Ni}^{2+}$ molar ratios, porous LFO was submerged in a solution that also included urea and Ni^{2+} . This allowed for the development of Ni compounds. Based on the data presented in Fig. 17a, the optimal sample had a $\text{Ni}^{2+}/\text{Fe}^{3+}$ ratio of 49 and contained approximately 15% nickel. The transmission electron micrographs that are displayed in Fig. 17b demonstrate that NiFe-LFO is composed of extremely thin amorphous nanosheets. On the other hand, given that a Ni^{2+} solution does not exhibit the creation of nanosheets, it is highly probable that the chemical formula that is most suited is FeOOH. As shown in Fig. 17c, the introduction of surface Ni doping resulted in an improvement in the catalytic performance. It was observed that NiFe-LFO displayed a significantly lower overpotential η when compared to LNO-FeOOH and Ni-doped LFO-FeOOH. Simulations based on density-functional theory suggest that the robust electrical interactions that take place at the composite interface are mostly responsible for the improved catalytic activity. Ni^{2+} doping causes a change in the electrical configuration of the LFO, which in turn increases the amount of electron transport that occurs at the interface between the two substances. Furthermore, it causes the d-band center of FeOOH to become more pronounced. In addition to this, it significantly boosts open educational resource activity.

These discoveries [91] present an opportunity to investigate new avenues for the study of enhanced OER electrocatalysts for the purpose of their application in renewable energy sources. Niss et al. (1996) conducted a study in which they examined two distinct catalytic designs in great detail. The purpose of this study was to gain an understanding of the various spatial arrangements that have an effect on the parameters of the OER. On the other hand, Sm-Zn-L only had a superficial application of Sm_2O_3 , whereas Sm-Zn-E displayed structural implantation of magnesium oxide. In every benchmark test, the Sm-Zn-E catalysts shown greater performance in comparison to the Sm-Zn-L catalysts. This was the case in terms of stability (40 h and 1000 cycles), overpotential (419 mV for 10 $\text{mA}\cdot\text{cm}^{-2}$), and Tafel slope (89 $\text{mV}\cdot\text{dec}^{-1}$). One possible

explanation for this is that the long-term agreements that are advantageous to Open Educational Resources are responsible for this. An increase in surface area, a reduction in surface defects, and an improvement in the optimization of the electronic assemblies of the surface-active sites were all outcomes of the combination of tiny clusters of Sm_2O_3 and ZnO. Based on these findings, it appears that the incorporation of Sm into catalysts is a feasible approach of reorganizing catalysts in order to improve their spatial performance [92].

8. Metal oxides based on polymers for end-use and reuse

OER/ORR, which stands for electrolysis of water using conductive polymers, is an innovative and interesting approach that creates sustainable energy without contributing to climate change [93]. This method is usually referred to as OER/ORR. Polymers that are conducting and have been enhanced with metal/metal O_xH_x have the ability to speed electron transmission, which makes them excellent for processes that include water splitting [94,87]. Metal-air secondary batteries, often known as MABs, are an attractive alternative for the development of future energy storage systems. They have the potential to have an energy density of approximately $1000\text{W}\cdot\text{hkg}^{-1}$. In an alkaline metal-air battery, the OER and ORR are responsible for regulating the air-positive electrode in the following ways [88]. Through a one-of-a-kind interaction with the polycyclic aromatic intermediate molecules that are generated during the thermal breakdown of PVC, the AAO template is responsible for the formation of the graphene structure (Equation (7)).



After polarizing the carbon/CFCO electrodes at a current of $+40\text{ mA}\cdot\text{cm}^{-2}$ in $4\text{ mol}\cdot\text{dm}^{-3}$ potassium hydroxide, we examined the oxygen evolution reaction (OER) endurance of the electrodes. There was a significant decline in the electrocatalytic activity of DB/CFCO, DB2400/CFCO, and pCNF1500/CFCO towards OER, as evidenced by the reduction in current densities at 1.7 V vs. RHE to 53%, 54%, and 67% of their respective original values [89]. This was observed in the electrocatalytic activity of these three materials. There was a reduction in the oxygen evolution reaction current as a consequence of the carbon corrosion that

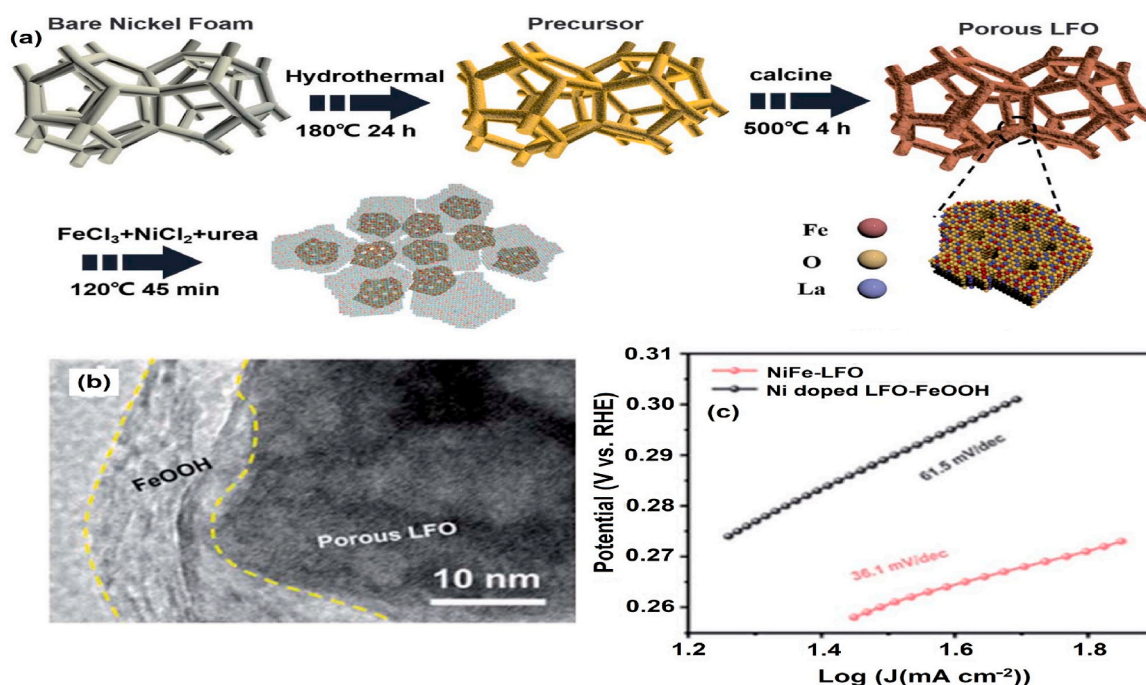


Fig. 17. The synthesis method of NiFe-LFO is schematically represented. (a) NiFe-LFO synthesis, (b) transmission electron microscopy picture, and (c) change in power density. Copyright from, the Royal Chemical Society 2021, [90].

occurred on the perovskite oxide/carbon electrodes. After the OER was deactivated, the current density of the MWCNT/CFCO electrode dropped to 87% at 1.7 V vs. RHE. This was the most significant decline. Despite this, the sample continued to have the highest level of graphitization and, as a result, indicated the highest level of resistance to oxidation [95].

When researchers put a nanocomposite electrocatalyst made of nickel oxyhydroxide and chitosan through its paces, they found that it performed exceptionally well in a wide range of electrocatalytic activities because of its composition. Organic redox reactions (ORR), organic electrochemical reactions (OER), and glucose oxidation (GO_x) were some of the activities that were involved in this process. It was previously shown that this nanocomposite had the ability to remove heavy metal ions from aqueous solutions by employing a variety of chitosan biosorbents [96], which led to its utilization in fuel cell applications. Initially, the electrical conductivity (EC) parameters of the composite in its as-prepared form were analyzed as part of this inquiry. The OER activity of electrodes made of calcined and uncalcined nano-NiOOH/GC was found to be higher than that of electrodes constructed of bare GC and CS/GC. It is clear from this discovery that NiOOH plays a significant role in the OER catalytic process. An improvement in the electrocatalytic activity of the OER was indicated by the rapid increase in the OER current and the large drop in the OER onset potential that occurred after annealing nano-CS-NiOOH/GC electrodes at a temperature of 250° Celsius [97]. The calcination temperature of nano-CS-NiOOH had an effect on the chemical structure of a catalyst as well as the electrocatalytic activity of the catalyst. The CS matrix was broken down at calcination temperatures that were higher than 280° Celsius, which resulted in an increase in the electrocatalytic activity of the nano-CS-NiOOH/GC electrode toward ORR and OER [98].

The development of electrocatalysts that are both highly efficient and cost-effective for the OER is required in order to improve the efficiency of water-splitting in electrocatalysis (EC). This study provides evidence that the inclusion of porous and self-supported FeNi-alloy fibers can result in significant reductions in overpotential, amazing stability, and extraordinary performance in the OER. OER stands for oxygen evolution reaction. The generation of hydrogen through electrochemical water splitting is a method that is both environmentally beneficial and long-lasting. It is also a method that may be used to store hydrogen. The technique that was described above makes use of renewable energy sources, notably wind and solar electricity [99]. Undergoing an OER at the anode electrode, water passes through a HER at the cathode electrode. Both of these reactions are referred to as evolution reactions. When compared to the two-electron transfer phases of the HER, the proton-coupled electron transfer mechanism of the oxygen evolution reaction (OER) ($4\text{OH} + 2\text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^-$) is more complicated and less efficient in the process of water splitting. This is because the OER involves the transfer of electrons from the proton to the electron. In order to get the desired results in organic electrolysis procedures, it is essential to make use of an electrocatalyst that is very efficient. At the moment, noble metal oxides, more specifically IrO_2 and RuO_2 , are the electrocatalysts that are the most effective for the oxygen evolution reaction (OER) [100,101]. According to the findings of the research, the OER kinetics in a lattice-oxygen-mediated mechanism (LOM) that makes use of perovskite oxide demonstrated greater performance when compared to the adsorbate evolution mechanism (AEM), which is the mechanism that is used the most frequently. Despite this, the goal of increasing the involvement of lattice oxygen continues to be a difficult and challenging one. The new OER electrocatalyst that our team has developed is represented by the symbol LSCFM, which stands for the elements lead, selenium, cobalt, fluoride, and methylene. The increased catalytic efficiency of the OER in LSCFM can be attributed to the larger concentration of surface oxygen vacancies and the accelerated air ion diffusion coefficient that it possesses. The aforementioned conclusion is supported by the findings that were obtained from XPS analysis, pH-dependent OER kinetics, and experiments that were carried out on

ionic diffusivity [102]. Using nanoparticle-sized $\text{La}_{0.8}\text{Sr}_{0.2}\text{MnO}_3$ (LSM) and a polymer-assisted chemical solution (PACS) approach, a network of perovskite catalysts was synthesized. The goal of this synthesis was to increase the activity of the OER while simultaneously retaining a high rate of ORR. The significance of open educational resources (OER) and open resource resources (ORR) in a variety of businesses and the advancement of technology has sparked a significant amount of interest in academic research. Comprehensive electrolyte testing was carried out across a pH range of 14 to 7 in order to assess whether or not it is possible to perform direct electrolysis of saltwater under conditions of virtually neutral pH [103]. Bi-functional catalysts that support both the OER and the HER are the focus of several emerging technologies. Among the materials that belong to the previously described groups are cobalt disulfide/graphite, NiFeS/NF , Co-Mo-B , perovskite nanostructures, and NiFeOx nanoparticles. RuO_2 is widely recognized as an OER catalyst, however its use in HER is not as extensive as it may be. The electrocatalytic efficacy of HER catalysts must be improved in order to solve the problems associated with reactivity, inadequate electron transport, limited surface area, and operational instability. Regarding the creation of sustainable energy systems, the quick development and research of new electrolytes that are extremely alkaline, the endurance of carbon nanostructures is dependent on the particular arrangement of the exposed carbon planes, which exhibit a significant level of graphitization. Platelet-type carbon nanofibers with a high degree of graphitization exhibit substantial promise as a robust material for air electrodes in metal-air batteries employing alkaline aqueous electrolytes. There is a considerable tendency for oxygen evolution processes, often known as OER, to oxidize iron atoms that are located on the surface. In order to rapidly adopt electrocatalysts that are efficient, cost-effective, and long-lasting, an alternative process known as electrochemical reconstruction of alloys can be utilized [104].

9. OER And HER metal oxides supported by MXenes

For the purpose of transforming MAX phases into the 2D MXenes family of transition metal carbides and nitrides, it is possible to accomplish this transformation through the utilization of a number of different etching and delamination processes [105,106]. The MAX phase is characterized from other phases by the presence of an early transition metal (M), an element (A) belonging to either group 13 or 14, and either carbon or nitrogen (X), as indicated by the general formula $\text{M}_{n+1}\text{AX}_n$. At this point, the carbide layers are terminated with OH, O, Cl, or F groups, which are commonly referred to as “surface groups” or “edge sites.” This occurs after the group 13/14 element has been removed from the MAX structure through the process of etching using a solvent that includes fluoride ions. It is common practice to refer to the final product as “MXene.” It is anticipated that the integration of pure metal oxides into a catalyst layer for the OER will be advantageous due to the enhanced conductivity, hydrophilicity, and tunability of MXenes. The potential of MXene materials for water-splitting in the HER has been established via the use of theoretical models and experimental methodologies [107–109]. This is despite the fact that this phenomenon occurs in the opposite direction. At the moment, researchers are conducting extensive research into the potential electrocatalytic capabilities of nanolaminate ternary transition metal carbides (also known as MAX phases) and two-dimensional transition metal carbides (known as MXenes). There are four distinct components that make up the core-shell MAX@MXene structures. These components include an MXene shell and a Co/Ni-MAX phase that is located in the middle of each structure. Because of its core-shell structure, $\text{Ta}_2\text{CoC}@ \text{Ta}_2\text{CTx}$ demonstrated remarkable stability in an alkaline electrolyte. This was demonstrated by an overpotential of 239 mV and the utilization of MXenes as the active sites. Utilizing surface reconstruction allowed for the preservation of the bulk crystalline structure of the $\text{Ta}_2\text{CoC}-\text{Ta}_2\text{CTx}$ core-shell structure, while simultaneously allowing for the creation of Co-based OxHs as active sites. The findings of the experiment showed that there was a little overpotential of

373 mV, and the Tafel plot had a value of 56 mV.dec^{-1} during the experiment. Within the context of programs pertaining to renewable energy, the current study provided the platform for future research on materials that make use of MAX phases. In addition, the research proposed a novel approach to the production of electrocatalysts that are capable of performing numerous functions, taking into account the diverse chemical compositions and structures of MAX phases [110]. In accordance with the explanation provided by Zou et al. [111], it illustrates the outcomes of the synthesis of a novel hierarchical porous NiCo mixed-metal sulfide (NiCoS) on Ti3C2Tx MXene by making use of a metal-organic framework (MOF). Due to the strong interfacial connections and distinctive architectures of the NiCoS and Ti3C2Tx sheets, the hybrid material has the potential to induce an increase in the OER. The OER studies revealed that the surface NiCoOOH was the primary active species responsible for water oxidation. This was determined by the findings of the experiments. Ultimately, the result is an assembly of NiCoOOH–NiCoS, which displays a unique variant from the hierarchical NiCoS that was discovered in the initial hybrid. The utilization of a hybrid material in the air cathode of rechargeable zinc-air batteries results in a minimal charging/discharging overpotential and demonstrates consistent performance over an extended period of time [111]. In this work, the relationship between the composition of catalysts that do not rely on noble metals and their functionality is investigated and found to be significant. Within the context of OER, this remark highlights the plasticity of MXenes in terms of altering the composition of MOF derivatives as well as the electrocatalytic efficiency of these derivatives. Within the scope of this investigation, the fabrication of CoS₂ nanowire composites was accomplished by utilizing the electronegative surfaces of exfoliated MXene nanosheets in conjunction with the HT reaction and sulfurization reactions. Compared to pure CoS₂ and MXene, the trifunctional electrocatalyst that was created by the CoS₂–MXene composite exhibited a lower overpotential for ORR, OER, and HER in alkaline solutions. This was one of the notable characteristics of the composite. Significant findings have been obtained by the use of multidimensional manufacturing techniques to the production of one-dimensional CoS₂ nanowires on a two-dimensional MXene substrate. These findings hold promise for the development of catalysts in energy conversion systems that do not rely on noble metals. The numbers [112–114]. It was demonstrated that the integration of MXene and phosphorization considerably increased the creation of active sites for high-valence transition metals by the production of a catalyst that was constituted of NiFeCoP/MXene. Alterations were performed to the electron configuration surrounding TM, which comprises components such as nickel, iron, and cobalt, in order to achieve this purpose. The subsequent step of the HT's development was followed by the implementation of an *in situ* phosphorization strategy. Furthermore, the electrochemical investigations indicated the simple generation of a large number of active species that are engaged in the OER, particularly NiOOH. Under conditions of a current density of 10.0 mA, the NiFeCoP/MXene material displayed a moderate overpotential of 240 mV.

10. Sturdy bases for metal oxides for OER and HER

One of the most remarkable properties of metal oxides and hydroxides is their electrocatalytic activity, which makes them exceptionally well-suited for inclusion into a wide variety of energy conversion and storage systems. Electrolysis is a process that involves the incorporation of metals and metal oxides into water in electrode systems that are dependent on substances of this kind. In electrocatalytic processes, one of the most important and noticeable stages is the generation of oxides and hydroxides on the surface area of electrodes [115–118]. The purpose of this article is to offer a comprehensive summary of the OER and HER catalytic activity of a number of metal OxHs that are supported on solids. According to the information provided in Refs. [119–123], the bimetallic OxHs with amorphous carbon, which are based on cobalt and iron, were supported by perovskites that contained Ba, Sr, and La. Due to

its greater oxidation rate and its capacity to keep the cobalt cation at the lower oxidation sites, iron (Fe) typically increases the oxygen evolution rate in cobalt OxH systems. This process is known as the oxygen evolution rate enhancement. Additionally, it was found that the OER was enhanced by the establishment of electrical contact between cobalt (Co) and iron (Fe) when the iron concentration of the BSCF perovskite was decreased. This was discovered through the determination of the fact that the OER was enhanced. In an investigation that was carried out by Yuan and colleagues, the performance of a three-dimensional NiFe-based OxHs supported nickel foam catalyst was examined in an electrolyte that was composed of KOH at a temperature of 80° Celsius. At a phenomenal OER activity of 10.0 mol.L^{-1} , the catalyst demonstrated exceptional performance. The functional groups that elicit either electron release (COOH and NO₂) or electron donation (–NH₂, –OH, and –OCH₃) are considered to be the primary focus of this catalytic activity. The augmentation and/or change of the interface between the electrode and the electrolyte that is the result of these capabilities can be linked to the increased electrocatalytic activity that has been observed. The use of *in situ* EC Raman spectroscopy allowed for the detection of the presence of FeOOH and NiOOH, which led to an extraordinarily high catalytic current density of 500 mA.cm^{-2} and extraordinary activity [124–127]. It was discovered that the OER activity of the NiFeOxH-anchored N-doped carbon aerogel was exceptional at a current density of 10 mA.cm^{-2} and a low electrode overpotential of 304 mV, as stated in the scientific publication [128]. Furthermore, studies that were conducted using Density Functional Theory (DFT) have provided evidence that the enhanced affinity of the metal (Ni–Fe) OxH towards carbon aerogel can be utilized to build a catalyst that is very effective for energy storage and conversion systems. By making use of electrocatalyst generation that is both effective and efficient, the slow electro-kinetics of the OER have been addressed. In addition, Yu et al. announced the completion of the synthesis of carbon black-attached NiFeOxH clusters, which is a noteworthy discovery in the field. As a result of the catalyst's improved nanostructure and increased surface area, it was able to exhibit spectacular OERs at an overpotential that was extremely low, measuring 320 mV. The high catalytic activity of Ni–O–Fe complexes in oxygen electrochemistry is supported by evidence that comes from both theoretical calculations and experimental findings [118]. The authors of reference [129] were successful in their attempt to synthesize nanowires made of nickel molybdenum oxide (NiMoO₄) that were strengthened with nanoflowers made of cobalt hydroxide. The result of this attempt was the development of an electrocatalyst that is extremely effective for the processes of water splitting.

10.1. Metal oxide and their synthesis

The synthesis of metal oxides has been accomplished through the application of a wide variety of methodological approaches (Fig. 18). It is possible to produce a metal oxo-hydroxide intermediate by the coprecipitation approach by utilizing a reaction between the precipitating medium and the metal salt. The addition of sodium hydroxide, potassium hydroxide, or tetra ethyl ammonium hydroxide results in the transformation of the oxo-hydroxide into the metal oxide species. The ultimate morphology and qualities of a photocatalyst are found to be determined by the pH of the alkaline solution as well as the type of the solution itself. The approach is cost-effective, and large quantities of zinc oxide are produced by employing this method. The development of an emulsion is accomplished using the micro-emulsion method by combining two layers of water and surfactant that are incompatible with one another, as well as oil and surfactant that contain a metal oxide precursor. Nanoparticles of metal oxide are produced as a consequence of the incorporation of a precipitating reagent into the mixture. In order to synthesize TiO₂ in the region of 30–50 nM using this process, modified procedures have been devised that have been modified. The process of hydrothermal synthesis involves the thermal breakdown of aqueous solutions of metal oxides. This can be accomplished by the use of

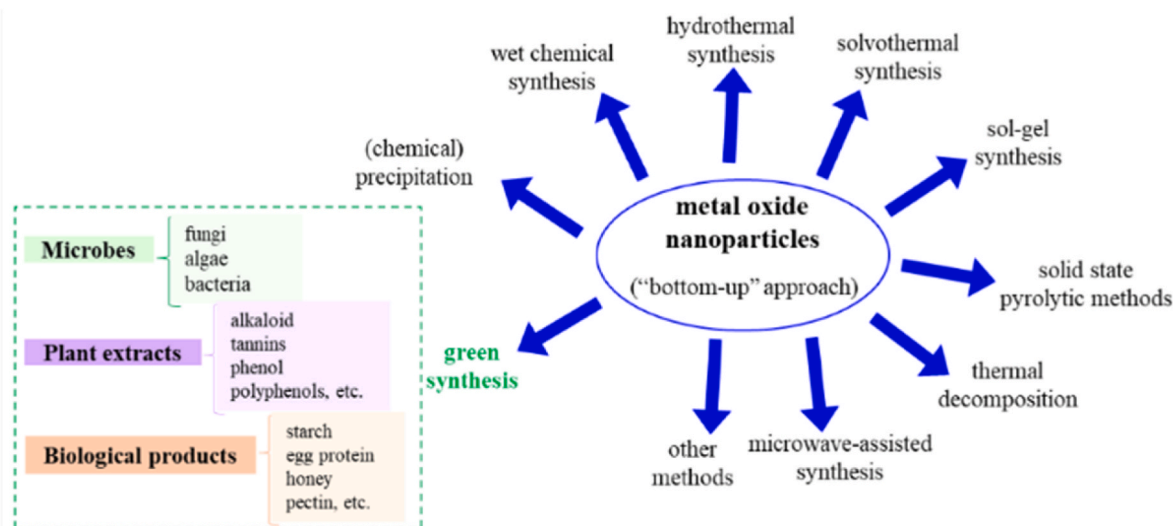


Fig. 18. Possible nano particle synthesis approaches [84], copy right from MDPI, J. Funct. Biomater. 2022.

autoclaving or by employing an inactive environment at room temperature. By incorporating stabilizers into the mixture, it is possible to prevent the particles from aggregating into larger groups. Sonochemical techniques involve applying ultrasonic vibrations to a solution of metal oxide in order to change its chemical composition. This results in heating of the solution which when cooled results in creation of the crystals of metal oxides. A mechanism known as acoustic cavitation is responsible for the accomplishment of the crystallization. The technique results in nanoparticles that are of a consistent size, have a high level of purity, and have a large surface area. Through the use of this technique, TiO_2 nanoparticles have been manufactured, and they have demonstrated an exceptionally high level of photocatalytic activity. Sol-gel technique is the most extensively used approach that involves the breakdown of metal alkoxides in ethanolic solution to generate hydroxides, which then polymerize to form a porous gel. This process is the most widely used method [84].

A direct hydrothermal (HT) technique was utilized by the researchers in order to put $\text{Co}(\text{OH})_2/\text{NiMoO}_4$ nanowires onto carbon fabric. This process resulted in the formation of one-dimensional nanostructures in electrolytes that included a concentration of 1.0 M KOH. An overpotential of 183 mV towards the heterojunction (HER) and 170 mV towards the OER demonstrated that the nanostructures displayed outstanding long-term stability when subjected to a current density of $10 \text{ mA}\cdot\text{cm}^{-2}$. At this current density, the nanostructures exhibited exceptional stability. Through the utilization of a hierarchical nanostructure that was composed of thin layers of nickel-iron oxides and hydroxide, a metallic alloy that contained both nickel and copper was successfully manufactured. In the OER, the alloy exhibited outstanding performance with an overpotential of 218 mV and a higher energy ratio (HER) of 66 mV. This was accomplished by utilizing a current density of $10 \text{ mA}\cdot\text{cm}^{-2}$. Furthermore, the catalyst that was synthesized displayed a voltage of 293 mV at a current density of $10 \text{ mA}\cdot\text{cm}^{-2}$ and 506 mV at a current density of $50 \text{ mA}\cdot\text{cm}^{-2}$, as recorded in Refs. [130–132]. This was accomplished by conducting an analysis using a solar-powered electrolyzer that was powered by 1.5 V. Through the utilization of tantalum OxHs in conjunction with Sr and $\text{BO}/(\text{OH})_x$, Lawley et al. (2013) were able to successfully utilize solar light to enhance the process of water splitting. It was discovered that the insertion of $\text{BO}/(\text{OH})_x$, in conjunction with the modified electrodes, resulted in an increase in the hydrophilicity of the catalyst on the outer surface. In addition, it was discovered that the incorporation of Sr into the catalyst led to an improvement in surface reconstruction as well as an increase in the effectiveness of the water-splitting process. Additionally, the OER demonstrated extraordinary catalytic activity, while the oxy-nitroxy

interfaces demonstrated an increase in light adsorption. For the purpose of the OER, the synthesis of N-doped carbon nanotubes (CNTs) was carried out with amorphous CoFe and double-hydroxide serving as support materials [133–137].

Applying a method that is both direct and ambient. By generating oxygen radicals, double hydroxide not only improves its catalytic characteristics in aqueous systems, but it also makes it easier to remove reactive oxygen species from the electrolyte solution. This is accomplished by the formation of oxygen radicals. It was determined that the increased faulty surface area of the amorphous metal hydroxide form was responsible for the significant rise in OER. In order to build a bifunctional nanoarchitecture consisting of SnFe sulphide and oxyhydroxide on nickel foam, a basic solvo-thermal approach was utilized [138,139]. This technique did not require the use of a binder. The performance of the electrocatalysts that were developed has shown good results, as proven by the decrease of the HER overpotential to 324 mV and the OER to 281 mV at a current density of $1000 \text{ mA}\cdot\text{cm}^{-2}$. Both of these reductions were achieved at a certain current density. In order to actively separate oxygen, the OER made use of an electro-catalytically active heterostructured interface that was situated between sulphide and oxyhydroxide respectively.

There were parallels to be drawn between the trend seen in oxoacid (C_2O_4) and the creation of a modifiable proton acceptor on NiOOH . The oxygen evolution reaction (OER) was improved as a result of the effective restoration of the active surface, which was composed of Ni metal complexes. This restoration was accomplished in a permanent way. Studies that were conducted in the past suggest that these acids may unintentionally boost the activity of the OER by 270 mV (10 mAcm^{-2}) by making it easier for the electrolyte to absorb protons or hydrogen ions [140–143]. The researchers hypothesize that other transition metals, such as cobalt (Co) and iron (Fe), might potentially be treated in a manner that is analogous to the one described above. The construction of gold nanoparticles (AuNPs) was carried out [144,145]. By maintaining the structure of OxH (CoOOH) in a hierarchical fashion, cobalt metal is responsible for its maintenance. Fig. 19a illustrates the method that is being used. During the course of the investigation, EC impedance spectroscopy (EIS) was applied to AuNPs/ CoOOH in order to acquire additional validation. In addition, the efficiency of the incident photo-electron conversion was confirmed to be up to 5% through the use of photo-assisted OER activity, as shown in Fig. 19b.

11. Conclusion

Scientists are always working to develop energy storage and

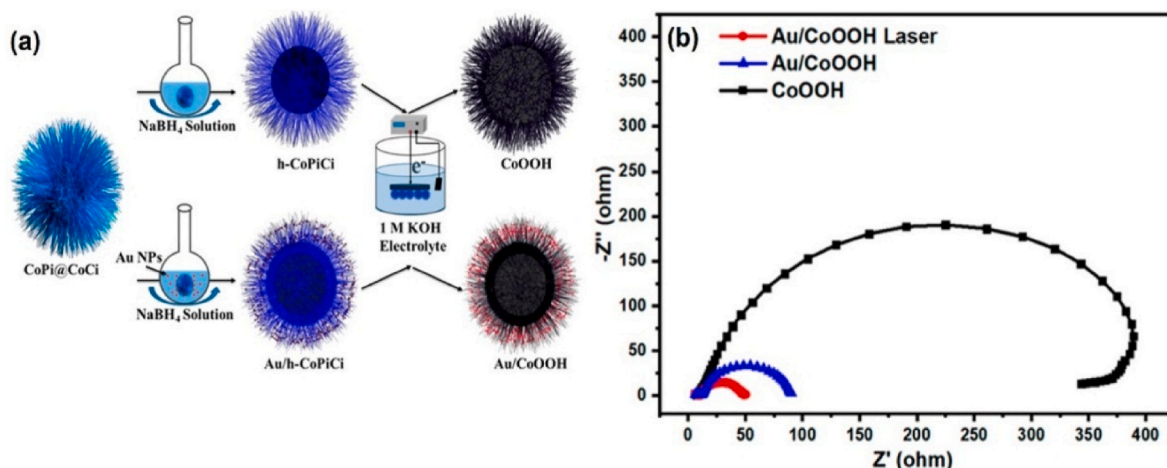


Fig. 19. (a) The synthetic route of Au/CoOOH- (b) EC impedance plots of CoOOH, Au/CoOOH, and Au/CoOOH. Copyright from the American Chemical Society 2020 [124].

conversion technologies that are cutting-edge, dynamic, and cost-effective in order to handle the growing demand for energy and the climate change that is linked with it. The examination of water electrolysis is now being carried out in order to investigate its potential for commercialization as a cost-effective alternative to existing technologies that are environmentally sustainable. By facilitating better electrode active kinetics in the processes of water splitting, oxygen evolution, and hydrogen evolution, advancements in catalyst design have made it possible to implement these processes. Additionally, the utilization of metal oxide electrode systems, which are distinguished by their longevity and exceptional quality, contributes to the enhancement of the effectiveness of the method. Electrocatalytic systems that facilitate the HER, OER, and water splitting are made possible by transition metals and the electrocatalysts that attach to them. These systems play an essential role in electron transfer reactions. In addition to manganese, nickel, iron, and cobalt, the metallic elements also include a number of additional elements. According to the findings of previous studies, the addition of alternative metals and their OxHs, carbon-based supports, or other metal oxides has the potential to alleviate the sluggishness that is observed in transition metals and their oxides. This paper offers a complete summary of the recent developments in support co-catalysts, MXenes, polymers, and other domains that are pertinent to the topic at hand. It is of the utmost importance to conduct a comprehensive mechanistic examination into the redox processes that involve water splitting. (i) *Take into consideration the possibility of putting these updates into action in order to improve the process.* (ii) *It is of the utmost importance to do research on the function that supports and co-catalysts play in the long-term stability of catalysts, as well as the influence that they may have.* (iii) *Additional essential tasks include the stabilisation of the OxHs and the guarantee that they will perform at their highest potential in response situations.*

The development of a catalyst that is extremely stable for water-splitting reactions ought to be the primary focus of research on oxide-hydride catalysts. Exceptional electrocatalytic activity, high electrical conductivity, a large number of active sites, and resistance to corrosion are all characteristics that this catalyst ought to incorporate. When looking for advanced catalysts for HER and OER, it is essential to have a full understanding of the mechanisms that are underneath the surface. The development of new electrocatalysts is typically dependent on activity-oriented trial-and-error methods. These methods can be improved by getting a full understanding of water splitting processes at a multiscale level when they are used. When it comes to understanding the catalytic mechanism and structural advancement of electrodes, particularly in the context of OER electrocatalysts, computational modelling and *in situ* spectroscopic investigation are two techniques that are quite

efficient. Electrocatalysts like this often involve the reconstruction of complex surface structures at a number of different redox phases or stages.

Significant progress has been achieved in the ongoing development of photoelectrochemical (PEC) water splitting for hydrogen production, especially in the creation and refinement of nanostructured metal oxide photoanodes. In conclusion, these advancements have been made. Several significant materials, including as titanium dioxide (TiO₂), tungsten oxide (WO₂), bivalent oxygen (BVO₂), and iron oxide (FeO₂), have demonstrated their potential for large-scale hydrogen generation as a result of their adequate bandgap energies, stability, and the possibility of harnessing solar energy. In spite of this, there are still a number of significant obstacles that need to be overcome before the potential of the PEC water splitting technology can be completely realized. Operando analytical methods that have been effectively used to track the surface species in OER include Fourier-transform infrared spectroscopy, Raman spectroscopy, and X-ray absorption spectroscopy. This aids in revealing the catalytic mechanism and the real catalytic active areas. The implications of band structure, density of states, hydrogen adsorption energy, and catalytic activity are discussed, and a summary of recent breakthroughs in electronic structure manipulation and TMC engineering for high-performance HER is provided. Additionally, a discussion of the ramifications of these factors is included. An overview of the typical modification techniques, which include strain, heterostructures, vacancies, doping, and phase change, is shown here. Doping primarily have an effect on the local electron distribution adjacent to heteroatoms, whereas vacancies are responsible for the appearance of defects. The degree of change has an effect on both the long-term stability and the catalytic activity of the material.

CRediT authorship contribution statement

Muhammad Naeem Ayub: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Umer Shahzad:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Muhammad Fazle Rabbee:** Writing – review & editing, Resources, Methodology, Investigation, Formal analysis. **Mohsin Saeed:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Mohammad Mizanur Rahman Khan:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Mohammed M. Rahman:** Writing – review & editing, Visualization, Supervision, Funding acquisition, Conceptualization.

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