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Review

Advancements in water splitting for sustainable energy generation: A review

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Abstract: Water splitting, the process of converting water into hydrogen and oxygen gases, has garnered significant attention as a promising avenue for sustainable energy production. One area of focus has been the development of efficient and cost-effective catalysts for water splitting. Researchers have explored catalysts based on abundant and inexpensive materials such as nickel, iron, and cobalt, which have demonstrated improved performance and stability. These catalysts show promise for large-scale implementation and offer potential for reducing the reliance on expensive and scarce materials. Another avenue of research involves photoelectrochemical (PEC) cells, which utilize solar energy to drive the water-splitting reaction. Scientists have been working on designing novel materials, including metal oxides and semiconductors, to enhance light absorption and charge separation properties. These advancements in PEC technology aim to maximize the conversion of sunlight into chemical energy. Inspired by natural photosynthesis, artificial photosynthesis approaches have also gained traction. By integrating light-absorbing materials, catalysts, and membranes, these systems aim to mimic the complex processes of natural photosynthesis and produce hydrogen fuel from water. The development of efficient and stable artificial photosynthesis systems holds promise for sustainable and clean energy production. Tandem cells, which combine multiple light-absorbing materials with different bandgaps, have emerged as a strategy to enhance the efficiency of water-splitting systems. By capturing a broader range of the solar spectrum, tandem cells optimize light absorption and improve overall system performance. Lastly, advancements in electrocatalysis have played a critical role in water splitting. Researchers have focused on developing advanced electrocatalysts with high activity, selectivity, and stability for the oxygen evolution reaction (OER) and hydrogen evolution reaction (HER). These electrocatalysts contribute to overall water-splitting efficiency and pave the way for practical implementation.

Keywords: water splitting; oxygen evolution reaction (OER); hydrogen evolution reaction (HER); photoelectrochemical (PEC) cells; scarce materials; catalyst

1. Introduction

In the quest for sustainable energy generation, the development of efficient and clean technologies is of paramount importance. Among the various renewable energy sources, hydrogen has emerged as a promising candidate due to its high energy content and versatility. Water splitting, a process that involves separating water into its constituent elements, hydrogen and oxygen, offers a viable pathway for the production

of hydrogen as a clean fuel [1,2]. Traditionally, water splitting has relied on electrolysis, a process that utilizes electricity to drive the reaction. However, electrolysis methods have faced challenges in terms of energy efficiency and cost-effectiveness, limiting their large-scale implementation [3,4]. To overcome these barriers, researchers and scientists around the world have been working diligently to break new ground in water splitting technology. In recent years, significant advancements have been made in the field of water splitting, leading to the development of novel and efficient approaches. These breakthroughs have the potential to revolutionize the renewable energy landscape and pave the way for a sustainable future [5,6].

One of the key areas of focus in water splitting research has been the development of catalysts. Catalysts play a crucial role in facilitating the water splitting reaction by reducing the energy requirements and increasing the reaction rates. Traditional catalysts, such as platinum, are effective but expensive, hindering their widespread adoption. However, researchers have made remarkable progress in developing low-cost and earth-abundant catalysts, such as transition metal oxides and molecular catalysts, which exhibit excellent catalytic activity and stability [7–9]. Another significant advancement in water splitting technology is the exploration of photoelectrochemical (PEC) cells. PEC cells utilize semiconductor materials to harness solar energy and drive the water splitting reaction. By combining light absorption and catalytic activity in a single device, PEC cells offer a promising approach to achieve solar-driven water splitting. Researchers have been actively investigating various semiconductor materials, such as metal oxides and perovskites, to enhance the efficiency and stability of PEC cells [10–12].

Furthermore, advancements in nanotechnology have opened up new avenues for improving water splitting efficiency. Nanostructured materials provide a high surface area, improved charge transport, and enhanced light absorption, making them ideal candidates for water splitting applications. Nanoparticles, nanowires, and nanotubes have demonstrated remarkable performance in catalyzing the water splitting reaction, offering unparalleled opportunities for efficient and cost-effective hydrogen production [13–15]. Moreover, the integration of water splitting technologies with renewable energy sources, such as wind and solar, holds tremendous potential for sustainable energy generation. By utilizing excess electricity generated from renewable sources during off-peak hours, water splitting can store the energy in the form of hydrogen, which can be used later for power generation or as a clean fuel for transportation [16–18].

Countries such as Japan, the United States, Germany, China, and South Korea have been actively researching and developing water splitting technologies [19]. They have made notable advancements in terms of increasing efficiency, reducing costs, and developing new materials for electrocatalysts [20]. Japan has a strong research community and has been actively collaborating with universities, research institutes, and industries to advance sunlight-driven water splitting technology [21]. Institutions such as the University of Tokyo, Kyoto University, and the National Institute of Advanced Industrial Science and Technology (AIST) have been at the forefront of this research. Japanese researchers have been working on the development of efficient and stable photoelectrochemical (PEC) cells and photoelectrodes for water splitting. The

United States has a vibrant research community dedicated to advancing water splitting technology. Many universities, national labs, and private research institutions have been conducting research to improve the efficiency, durability, and cost-effectiveness of water splitting systems [22]. Electrolysis, particularly proton exchange membrane (PEM) electrolysis and solid oxide electrolysis cells (SOEC), has been an area of focus in the USA. Besides this, researchers have been working on developing efficient and stable photoelectrodes, exploring new materials, and improving light absorption and charge separation processes. In addition, Germany, China, and South Korea have been actively researching and developing water splitting technologies [23,24].

In a short, advancements in water splitting technology are breaking the barriers that have hindered its widespread implementation for sustainable energy generation. The development of efficient catalysts, exploration of photoelectrochemical cells, utilization of nanostructured materials, and integration with renewable energy sources are propelling the field forward. These advancements offer a promising pathway towards a clean and sustainable future, where hydrogen can play a vital role in meeting our energy needs while minimizing environmental impact.

2. Development of efficient and cost-effective catalysts for water splitting

Water splitting is a promising technology for producing clean and renewable hydrogen fuel. It involves the separation of water into hydrogen and oxygen gases through electrochemical reactions. The process typically requires the use of catalysts to enhance the reaction rates and efficiency. Over the years, researchers have been working on developing efficient and cost-effective catalysts for water splitting.

2.1. Platinum group metals (PGMs)

PGMs, particularly platinum and iridium, have traditionally been used as catalysts for water splitting. However, their high cost and limited availability hinder large-scale applications. Researchers are exploring ways to reduce or replace the use of PGMs with more abundant and cost-effective materials [25–27].

2.2. Earth-abundant catalysts

Efforts have been focused on developing catalysts based on earth-abundant elements, such as transition metal oxides, sulfides, phosphides, and nitrides. These materials offer the advantages of low cost and scalability. For example, metal oxides like iron oxide (Fe_2O_3) and cobalt oxide (Co_3O_4) have shown promising catalytic activity [28–30]. An illustration of catalysis by earth-abundant materials is shown in **Figure 1**.

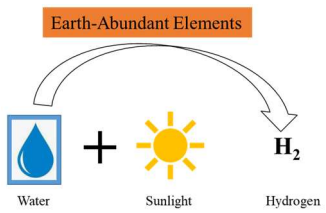

Figure 1. Water splitting with earth-abundant elements.

2.3. Bimetallic and alloy catalysts

Combining different metals into bimetallic or alloy catalysts can enhance their catalytic properties. For instance, combining nickel (Ni) with iron (Fe) or cobalt (Co) has shown improved activity for water splitting. These catalysts can be synthesized using various methods, including electrochemical deposition, sol-gel techniques, and physical mixing [31–33].

2.4. Molecular catalysts

Researchers are also exploring molecular catalysts, especially based on abundant and inexpensive organic compounds. These catalysts typically contain metal complexes with ligands that facilitate the water splitting reactions. A molecular catalytic reaction is demonstrated in **Figure 2**. Molecular catalysts offer precise control over the catalytic properties and can be designed to optimize efficiency [34–36].

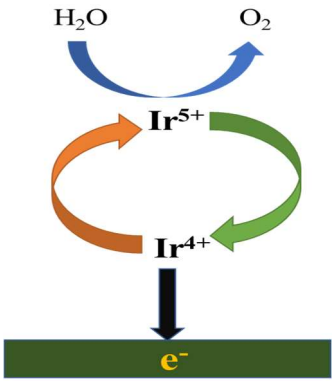

Figure 2. Schematic diagram of homogeneous catalysis with soluble molecular catalyst.

2.5. Nanostructured catalysts

Nanostructured catalysts, such as nanoparticles, nanowires, and nanotubes, have attracted attention due to their high surface area and unique electronic properties. These structures can enhance catalytic activity by providing more active sites and improving charge transport. Examples include metal nanoparticles supported on conductive substrates or semiconductor nanomaterials [37–40]. Several nanoparticles and nanowires are shown in **Figure 3**.

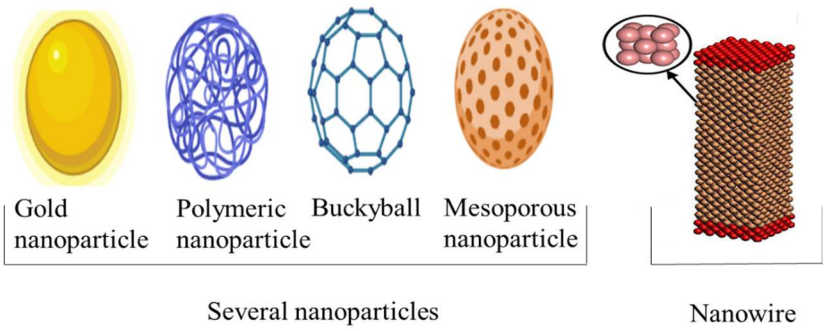

Figure 3. An illustration of nanoparticles and nanowire.

2.6. Computational design

Advances in computational modeling and machine learning have enabled the rational design of catalysts with enhanced activity. By simulating the electronic structure and reaction kinetics, researchers can identify promising catalyst candidates for experimental validation, accelerating the discovery process [41–43].

3. Solar energy to drive the water-splitting reaction

Utilizing solar energy to drive the water-splitting reaction is a promising approach for sustainable hydrogen production. It involves harnessing the energy from sunlight and converting it into chemical energy stored in the form of hydrogen gas. There are two common methods for using solar energy in water splitting:

3.1. Photovoltaic (PV) electrolysis

This method involves using photovoltaic cells, commonly known as solar cells, to directly convert solar energy into electricity. The generated electricity is then used to power an electrolyzer, which splits water into hydrogen and oxygen gases. The electrolyzer consists of two electrodes (cathode and anode) immersed in an electrolyte solution. When an electric current is applied, water molecules at the cathode are reduced to produce hydrogen gas (H_2), while water molecules at the anode are oxidized to produce oxygen gas (O_2). Catalysts are employed at the electrodes to enhance the reaction rates and improve overall efficiency [44–46].

3.2. Photoelectrochemical (PEC) water splitting

PEC water splitting combines the principles of solar cells and electrolysis into a single device. A photoelectrochemical cell is used, which typically consists of a semiconductor electrode immersed in an electrolyte solution [47]. A schematic diagram of photoelectrochemical water splitting is depicted in **Figure 4**. The semiconductor electrode absorbs photons from sunlight, generating electron-hole pairs. The excited electrons participate in the reduction reaction (hydrogen evolution), while the holes contribute to the oxidation reaction (oxygen evolution) [48–51]. Catalysts are essential in PEC cells to facilitate the reaction kinetics and improve efficiency. Both PV electrolysis and PEC water splitting have their advantages and challenges:

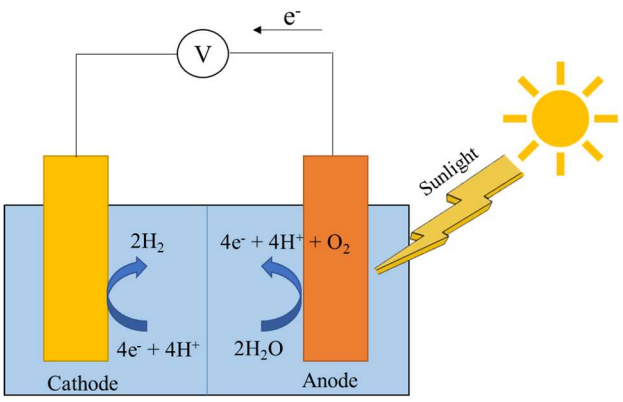

Figure 4. Schematic diagram of photoelectrochemical water splitting.

3.2.1. Advantages

- Utilization of abundant and renewable solar energy.
- Production of clean and sustainable hydrogen fuel.
- Compatibility with existing infrastructure for hydrogen storage and utilization.
- Potential for decentralized hydrogen production.

3.2.2. Challenges

- Efficiency: Maximizing the efficiency of solar energy conversion and the water-splitting reaction to maximize hydrogen production.
- Catalysts: Developing efficient and stable catalysts that can enhance the reaction rates and reduce energy losses.
- Materials: Exploring and optimizing semiconductor materials with desirable properties for efficient solar energy absorption and charge separation.
- Durability: Ensuring the long-term stability and durability of the materials and catalysts under harsh operating conditions.
- Cost: Reducing the cost of materials, catalysts, and system components to enable widespread adoption.

Ongoing research and development efforts are focused on improving the efficiency, stability, and cost-effectiveness of solar-driven water-splitting technologies. By addressing these challenges, solar energy can be harnessed to drive the water-splitting reaction, enabling the production of clean and sustainable hydrogen fuel.

4. Natural photosynthesis to hydrogen fuel

By integrating light-absorbing materials, catalysts, and membranes, artificial photosynthetic systems aim to mimic the complex processes of natural photosynthesis and produce hydrogen fuel from water. These systems, often referred to as artificial photosynthesis or artificial leaf systems, seek to harness solar energy and use it to drive the water-splitting reaction, generating hydrogen gas (H_2) as a clean and renewable fuel. Here's a breakdown of the key components:

4.1. Light-absorbing materials

Light-absorbing materials, such as semiconductors or molecular dyes, capture sunlight and convert it into usable energy. These materials should have a broad absorption spectrum, efficient light harvesting, and good charge separation properties to generate the necessary energetic electrons [52–54].

4.2. Catalysts

Catalysts facilitate the water-splitting reaction by reducing the energy barriers and increasing the reaction rates. They are typically used at the cathode (hydrogen-evolving reaction, HER) and anode (oxygen-evolving reaction, OER) to promote the respective electrochemical reactions. Catalysts can be based on various materials, including earth-abundant metals, metal oxides, molecular complexes, or even biological enzymes [55–57].

4.3. Membranes

Membranes are employed to separate the HER and OER compartments, preventing the mixing of hydrogen and oxygen gases and enhancing the overall system efficiency. Proton-exchange membranes (PEMs) or other selective ion-conductive membranes are used to enable the transport of protons while blocking the crossover of gases [58–60].

4.4. Electron transfer pathways

Efficient pathways for electron transfer are essential to transport the generated electrons from the light-absorbing materials to the catalytic sites. Electron-conductive materials or structures, such as conductive electrodes or nanowires, are used to facilitate the movement of electrons to the respective electrodes [61–63].

By integrating these components, artificial photosynthetic systems emulate the fundamental processes of natural photosynthesis, where plants and algae convert sunlight, water, and carbon dioxide into chemical energy in the form of carbohydrates. In the case of artificial photosynthesis for hydrogen production, the focus is on generating hydrogen fuel from water using sunlight as the primary energy source. These systems hold promise for sustainable and carbon-neutral energy production, but there are still challenges to overcome, such as improving the efficiency, stability, and scalability of the components, as well as reducing costs. Extensive research and development efforts are ongoing to advance the field of artificial photosynthesis and enable its practical implementation as a viable technology for hydrogen production and energy storage.

5. Tandem cells to enhance the efficiency of water-splitting systems

Tandem cells have emerged as a strategy to enhance the efficiency of water-splitting systems in artificial photosynthesis. Tandem cells are multi-junction devices that combine multiple light-absorbing materials with different bandgaps in a stacked configuration [64–66]. This configuration allows for the efficient capture of a broader range of the solar spectrum, thereby increasing the overall energy conversion efficiency. Here's a closer look at how tandem cells work:

5.1. Bandgap combinations

Different semiconductor materials have different bandgaps, which determine the range of light wavelengths they can efficiently absorb. In tandem cells, materials with varying bandgaps are carefully selected and arranged in a series to create a cascade of absorption layers. The bandgap of each layer is tailored to match the energy level of a specific portion of the solar spectrum, enabling efficient utilization of a wider range of photons [67,68].

5.2. Efficient light harvesting

As sunlight passes through the tandem cell, each layer absorbs a specific portion of the solar spectrum. The absorbed photons generate electron-hole pairs (excitons) in the respective layers, leading to the production of electrical current [69,70]. The light harvesting technique is demonstrated in **Figure 5**.

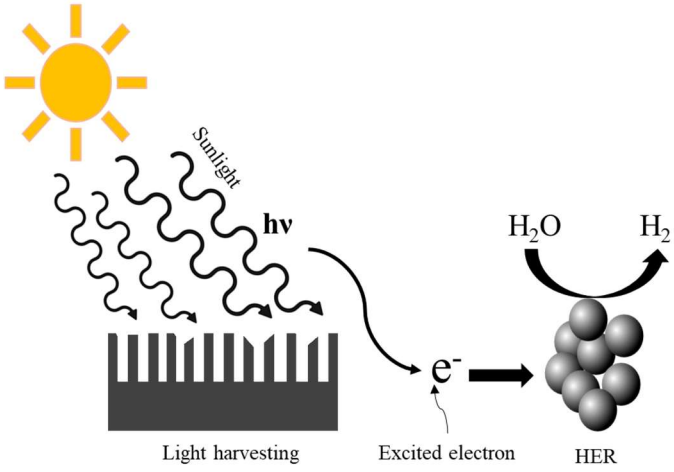

Figure 5. Light harvesting technique.

5.3. Charge separation and collection

The excited electrons and holes generated in each layer are rapidly separated due to the different bandgaps and internal electric fields. Efficient charge collection mechanisms are employed to extract the electrons and holes from each layer and direct them to their respective contacts or electrodes.

5.4. Water-splitting reactions

The separated electrons and holes can be utilized for the water-splitting reaction. The excited electrons are directed to the cathode, where they participate in the reduction reaction (hydrogen evolution) by converting protons (H^+) from water into hydrogen gas (H_2). The holes are directed to the anode, where they participate in the oxidation reaction (oxygen evolution) by oxidizing water molecules (H_2O) to produce oxygen gas (O_2).

By combining materials with different bandgaps in tandem cells, a larger portion of the solar spectrum can be effectively harvested, leading to improved light-to-hydrogen conversion efficiency. This approach allows for better utilization of solar energy and has the potential to achieve higher efficiencies compared to single-junction devices. Tandem cells are an active area of research, and scientists are exploring various material combinations, device architectures, and fabrication techniques to optimize their performance. The development of efficient and stable tandem cells is crucial for advancing the field of artificial photosynthesis and enabling more efficient solar-driven water-splitting systems for sustainable hydrogen production.

6. Development and optimization of OER and HER

The development and optimization of the oxygen evolution reaction (OER) and hydrogen evolution reaction (HER) electrocatalysts are crucial for advancing various energy conversion and storage technologies. Here are some key aspects involved in the development and optimization of OER and HER processes:

6.1. Catalyst screening and design

Initial stages involve screening and evaluation of various catalyst materials to

identify candidates with high activity for OER and HER. The catalyst design considers factors such as electronic structure, surface area, crystal structure, and surface chemistry to enhance catalytic activity and stability. Computational modeling and high-throughput screening techniques are often employed to accelerate catalyst discovery [71,72].

6.2. Nano-structuring and surface modifications

Nano-structuring techniques, such as nanoparticle synthesis, thin-film deposition, or nanowire fabrication, are employed to increase the surface area and expose more active sites. Surface modifications, such as doping, alloying, or surface functionalization, can tailor the catalyst's electronic properties and surface reactivity, leading to improved performance [73–75]. Surface functionalization of catalysts is illustrated in **Figure 6**.

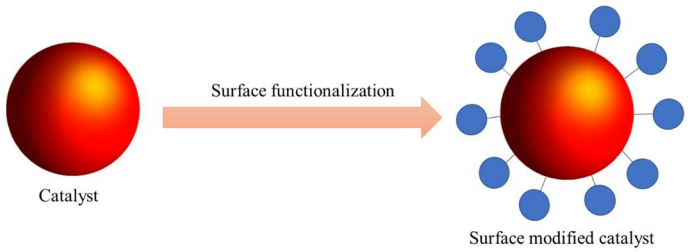

Figure 6. Surface functionalization of catalyst.

6.3. Interface engineering

The catalyst-support interface plays a crucial role in the overall catalytic activity and stability. Interface engineering techniques, such as optimizing the catalyst-support interaction, introducing interlayers, or using conductive substrates, can enhance electron transfer kinetics and catalytic performance [76–78].

6.4. Co-catalysts and synergy effects

Co-catalysts, such as metal nanoparticles, metal oxides, or molecular complexes, can be combined with the primary catalyst to enhance catalytic performance. Synergistic effects between different catalyst components can promote electron transfer, modify reaction kinetics, and improve overall efficiency [79,80].

6.5. Ion and mass transport

Efficient ion and mass transport within the electrochemical system is crucial for optimizing OER and HER. Strategies to enhance mass transport include designing porous electrode structures, optimizing electrolyte composition, and improving gas diffusion pathways [81,82].

6.6. Stability and durability

Long-term stability and durability of OER and HER catalysts are essential for practical applications. Researchers focus on understanding degradation mechanisms, developing strategies to mitigate catalyst degradation (e.g., corrosion resistance), and exploring protective coatings or encapsulation techniques [83,84].

6.7. Advanced characterization techniques

Advanced characterization techniques, such as scanning electron microscopy (SEM), transmission electron microscopy (TEM), X-ray photoelectron spectroscopy (XPS), and in-situ spectroscopy, provide insights into catalyst structures, active sites, and reaction mechanisms. These techniques help in understanding the structure-activity relationships and guide catalyst optimization efforts.

The development and optimization of OER and HER catalysts involve a multidisciplinary approach, combining materials science, surface chemistry, electrochemistry, and computational modeling. Continued research efforts aim to enhance catalytic activity, selectivity, stability, and cost-effectiveness to enable efficient and sustainable energy conversion and storage systems.

7. Catalyst for OER and HER

Researchers have indeed focused on developing advanced electrocatalysts with high activity, selectivity, and stability for the oxygen evolution reaction (OER) and hydrogen evolution reaction (HER). These electrocatalysts play a critical role in facilitating efficient and sustainable water splitting, which is essential for various applications, including artificial photosynthesis and renewable energy storage. Here's an overview of the advancements in electrocatalyst development for the OER and HER:

7.1. Oxygen evolution reaction (OER)

7.1.1. Metal oxides and mixed metal oxides

Metal oxides, such as ruthenium oxide (RuO_2), iridium oxide (IrO_2), and manganese oxide (MnO_x), have shown excellent catalytic activity for the OER. Researchers have been exploring the synthesis of nanostructured and well-defined metal oxide catalysts to enhance their surface area and expose more active sites. Mixed metal oxides, combining different elements, can exhibit improved OER activity and stability compared to single-metal oxides [85–87] (**Table 1**).

Table 1. Comparison of oxygen evolution reaction (OER) performance with various transition metal oxide and hydroxide [88].

Materials	pH	Overpotential for 10 mA cm^{-2}/V	Tafel Slope/mV $decade^{-1}$
MnCo-G	14	0.33	48
RuO_2	14	0.3	42
Ni_5Mn-LDH-MWCNT	14	0.35 (iR-corrected)	83
Co_5Mn-LDH-MWCNT	14	0.3 (iR-corrected)	74
CoNi-LDH/Fe-PP-M	14	0.32	53
$CuCo_2O_4$/N-rGO	14	0.36	64
Co_3S_4@MoS_2	14	0.33	59
$CoMoO_4$	14	0.31	56
CoP	14	0.36	66
CoFe LDH	13	0.36	49
NiFe LDH	14	0.33	41

7.1.2. Perovskite oxides

Perovskite oxides, with a general formula of ABO_3, have garnered significant attention for OER electrocatalysis. Materials such as strontium titanate ($SrTiO_3$), strontium iridate ($SrIrO_3$), and barium strontium cobalt iron oxide (BSCF) have demonstrated promising OER activity. Doping, surface modification, and nano structuring techniques are employed to optimize the performance of perovskite oxides [89–92].

7.1.3. Earth-Abundant talysts

To overcome the cost and scarcity associated with noble metals, researchers are actively exploring earth-abundant catalysts for the OER. Materials like cobalt-based compounds (e.g., Co_3O_4), nickel-iron-based compounds (e.g., NiFe layered double hydroxides), and metal phosphides (e.g., nickel phosphide, cobalt phosphide) have shown promising OER activity [93,94].

7.2. Hydrogen evolution reaction (HER)

7.2.1. Platinum group metals (PGMs)

PGMs, particularly platinum (Pt) and palladium (Pd), are highly efficient HER catalysts due to their excellent activity and stability. Researchers are working on developing advanced Pt- and Pd-based catalysts with enhanced activity through alloying, nano structuring, and developing hybrid materials.

7.2.2. Earth-abundant catalysts

To address the cost and sustainability issues associated with PGMs, researchers are actively exploring earth-abundant alternatives for HER. Materials such as transition metal sulfides (e.g., molybdenum sulfide, nickel-molybdenum sulfide) and metal phosphides (e.g., nickel phosphide, cobalt phosphide) have shown promising HER activity [93,94]. Several earth-abundant catalysts and their properties are shown in **Table 2**.

Table 2. Examples of earth-abundant HER electrocatalysts.

Catalyst material	η at −10mAcm^{-2} (mV)	Tafel slope (mV per decade)	pH	Faradaic yield
NiMo	200 (100 mAcm^{-2})	122	14.8	NA
CoMo	170 (100 mAcm^{-2})	92	14.8	NA
NiMo	185 (100 mAcm^{-2})	112	14.8	NA
NiMo	70 (20 mAcm^{-2})	NA	14.3	NA
NiMo	34 (20 mAcm^{-2})	NA	14	NA
MoS_2	260	50	0	NA
Pt	50	140–150	13	NA
Ni	58	81.6	14	NA
Mo	65	76	14	NA
MoS_2	200 (15 mAcm^{-2})	40	−0.3	100%*
MoS_2	~150	41	0	NA
MoS_2	170	60	0.2	NA
CoS_2	145	51	0	NA

Table 2. (*Continued*).

Catalyst material	η at −10 mAcm^{-2}(mV)	Tafel slope (mV per decade)	pH	Faradaic yield
CoS_2	~175	93	7	100%
CoMoSx	250	85	7	−100%
WS_2	~250	60	0	NA
$CoSe_2$	90	39	0	NA
MoS1.0Sel.0	~200	56	0	100%*
$NiSe_2$	~140	49	0	NA
Ni_2P	130 (20 mAcm^{-2})	46	0	100%*
CoP	85 (20 mAcm^{-2})	50	0	100%*
FeP	55	38	0	100%
MoP	64	NA	0	100%
CoNx	170	75	14	NA
CoNx	140	30	0	NA
NiMoNx	225 (5 mAcm^{-2})	35.9	1	NA
α-MoB	~225(20 mAcm^{-2})	55	−0.3	100%
Mo_2C	130	53	0	NA
MoC	124	43	0	NA
MoC	77	50	14	NA
Ni/C	34	41	0	100%*
$Cu_{95}Ti_5$	60	110	13	NA

7.2.3. Molecular catalysts

Molecular catalysts, typically based on metal complexes or metalloporphyrins, offer precise control over the active sites and electronic properties. Researchers are designing and synthesizing molecular catalysts with tailored structures to optimize HER activity, selectivity, and stability.

The development of advanced electrocatalysts with high activity, selectivity, and stability is crucial for improving the overall efficiency and commercial viability of water-splitting technologies. Researchers continue to explore new materials, catalyst designs, and strategies to enhance the performance of electrocatalysts for the OER and HER, aiming to enable efficient and sustainable hydrogen production.

8. Conclusion

In conclusion, significant progress has been made in the development and optimization of catalysts and technologies for water splitting, which has advanced the production of sustainable energy. Catalysts based on abundant and inexpensive materials, such as nickel, iron, and cobalt, have shown improved performance and stability, reducing the need for costly materials. Photoelectrochemical (PEC) cells, which utilize novel materials like metal oxides and semiconductors, aim to maximize the conversion of solar energy into chemical energy for water splitting. Artificial photosynthesis approaches, inspired by natural photosynthesis, integrate light-absorbing materials, catalysts, and membranes to produce hydrogen fuel from water, offering a potential solution for clean energy production. Tandem cells, which

combine multiple light-absorbing materials, optimize light absorption and enhance system efficiency. Furthermore, advancements in electrocatalysis have led to the development of advanced electrocatalysts with high activity, selectivity, and stability for the oxygen evolution reaction (OER) and hydrogen evolution reaction (HER). These advancements collectively pave the way for the practical implementation of water splitting in various energy conversion and storage systems, bringing us closer to a sustainable and clean energy future.

Conflict of interest: The authors declare no conflict of interest.

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