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Electrode selection and catalyst evaluation in hydrogen production from alkaline water electrolysis: A review

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Abstract

Generating hydrogen, through alkaline water electrolysis shows promise as an energy source. This review delves into the significance of choosing the electrodes and evaluating catalysts to enhance the efficiency and performance of hydrogen production. It summarizes the activation energy and losses linked to reactions in alkaline electrolysis emphasizing the necessity for electrode materials and catalysts. The review also touches upon challenges such as electricity consumption and platinum group metal based electro catalysts proposing various electrode materials and catalysts with superior activity and selectivity for hydrogen production. Additionally, it discusses electrolysis cell designs that facilitate separating by-products from hydrogen gas. The study reveals that with low over potentials of 70, 318, and 361 mV at 10, 500, and 1000 mA·cm^{-2}, respectively, NiOx/NF exhibits strong alkaline hydrogen evolution activity, resulting in great performance in alkaline HER. Moreover, it outlines advancements in alkaline water electrolysis technology focusing on enhanced efficiency and reduced operating costs associated with electricity consumption. Overall this review underscores the role of selecting electrodes and evaluating catalysts in optimizing hydrogen production from alkaline water electrolysis.

Keywords
hydrogen production, electrolysis, electrode selection, catalyst evaluation, electrochemical performance

1. INTRODUCTION

Different techniques are used to generate hydrogen, such as natural gas reformulation, coal gasification, water electrolysis and biomass gasification. Although steam methane reformulation known as SMF is a method for producing hydrogen and contributes to 48 percent of the total output, it is associated with carbon dioxide emissions. Another popular method involves coal gasification which leads to the production of greenhouse gas emissions (Dincer and Acar, 2014). Biomass gasification offers an approach by transforming substances into hydrogen yet there are obstacles to overcome in terms of its scalability and financial feasibility (Balat and Kırtay, 2010).

The process of water electrolysis involves splitting water into hydrogen and oxygen using electricity. It is becoming more popular due to its ability to produce hydrogen with the help of energy sources such as wind power and solar energy (Glenk and Reichelstein, 2019). This approach has no emissions, to its credit. Green hydrogen is valuable for its potential to reduce carbon footprints in areas like transportation and industry and for enabling energy storage in line with climate goals and is a move towards greener economy. As the world strives to address the impacts of climate change, green hydrogen emerges as a solution to reduce carbon footprints and bolster energy security. Fig. 1. shows the impact of hydrogen production on different sectors.

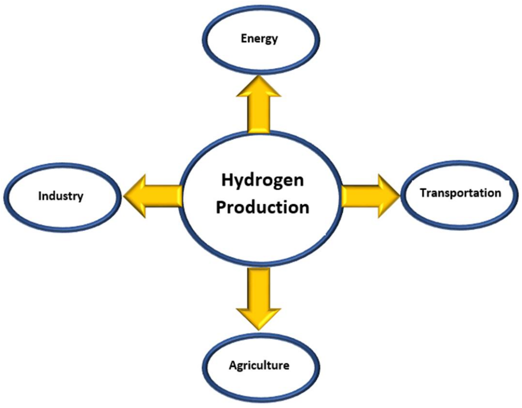

Figure 1. Effect of hydrogen production on other sectors.

Alkaline water electrolysis (AWE) is recognized for its role in hydrogen production because of its established technology that boasts efficiency and cost effectiveness benefits. On the other hand, when compared to hydrogen production techniques such as steam methane reforming alkaline water electrolysis generates hydrogen without emitting greenhouse gases as long as the electricity source is renewable (Dincer and Acar, 2014). This aspect makes AWE a vital technology for reducing carbon footprints and addressing climate change. Furthermore, AWE systems operate at temperatures and pressures which improve their safety and reliability compared to electrolytic techniques (Zeng and Zhang, 2010).

The scalability and simplicity of AWE systems play a role in their adoption especially in integrating intermittent renewable energy sources such as wind and solar power (Götz et al., 2016). Additionally, using precious metal catalysts in AWE reduces overall costs making it economically feasible for large scale hydrogen production (Carmo et al., 2013). The adaptability of AWE means it can be utilized in different sizes and applications ranging from de-centralized units to large industrial facilities. It further emphasizes its significance in the global shift towards a hydrogen based economy (Bhandari et al., 2014). As nations work towards achieving their energy goals, AWE emerges as a technology enabling the sustainable production of green hydrogen.

The main goal of this review is to analyse the selection of electrodes and evaluate that of catalysts in alkaline water electrolysis (AWE), a crucial technology for hydrogen generation. This review aims to gather and summarize research results emphasizing the performance characteristics, benefits and drawbacks of electrode materials and catalysts utilized in AWE. By delving into both the properties and practical uses this review aims to pinpoint the most promising materials that can enhance efficiency, durability and cost effectiveness (Zeng and Zhang, 2010).

Moreover, the review will delve into progress in composite electrodes along with hybrid catalysts that have displayed significant potential in enhancing the overall performance of AWE systems (Carmo et al., 2013). Another important objective is to scrutinize the methods used for assessing the physical properties of these materials, evaluating these techniques and their applicability, in real-world scenarios (Bhandari et al., 2014). By addressing these aspects, the review aims to steer research directions and bolster the advancement of effective and economically viable AWE technologies thereby supporting global initiatives aimed at promoting green hydrogen production (Götz et al., 2016).

2. FUNDAMENTALS

Electrolysis uses energy to facilitate a chemical reaction that would not occur spontaneously. The core concept involves passing a current through an electrolyte prompting ions to move towards the electrodes and triggering oxidation and reduction reactions. In the context of water electrolysis, water (H2O) gets separated into hydrogen (H2) and oxygen (O2) gases. The overall reactions at anode and cathode are represented by Equations (1) and (2) respectively;

$$2H_2O \rightarrow 4H^+ + O_2 + 4e^- \tag{1}$$

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \tag{2}$$

The thermodynamic efficiency of this process depends on the Gibbs free energy change while practical efficiency also considers potentials to losses over an alkaline water electrolyzer, activation energy barriers and mass transport limitations (McCrory et al., 2013). The alkaline water electrolyzer consists of key components: the anode, where oxygen evolution occurs; the cathode, where hydrogen is produced; and the electrolyte, typically an alkaline solution (KOH or NaOH), facilitating ion transfer between the electrodes. A separator/membrane prevents the mixing of hydrogen and oxygen gases. Optimal selection of materials and catalysts can greatly boost reaction rates and decrease energy consumption levels thereby making the process more efficient and cost effective (Schmidt et al., 2017). To make electrolysis systems work effectively for hydrogen production it is important to grasp the principles involved. These days bimetallic transition metal phosphides are becoming known for their efficiency as catalysts in generating hydrogen (Li et al., 2021; Schmidt et al., 2017).

This solution enables the transport of ions between electrodes by providing ionic conductivity. A separator, typically crafted from materials like asbestos or synthetic polymers plays a role in preventing the mixing of hydrogen and oxygen gases while allowing ion passage (Bailera et al., 2017). The cell casing, usually made from materials like steel or specific plastics resistant to electrolyte corrosion houses these components securely (Zeng and Zhang, 2010).

Moreover, additional components such as gas diffusers, current collectors and cooling systems can be included in the cell to ensure operation and maintain temperature conditions (Götz et al., 2016). Careful selection and configuration of each component are vital to enhance efficiency and longevity of the electrolysis cell, for hydrogen production (McCrory et al., 2013).

3. ELECTRODE MATERIALS

In alkaline water electrolysis, the choice of materials improves the efficiency, durability and cost effectiveness of hydrogen production. Metals like nickel (Ni) and iron (Fe) are commonly preferred due to their activity and cost effectiveness. Nickel is favoured for its stability in alkaline conditions (Zeng and Zhang, 2010). Metal alloys such as nickel iron (Ni Fe) and nickel cobalt (Ni Co) are also used to enhance properties and resistance to corrosion. Ni Fe alloys for example are well known for their performance in the oxygen evolution reaction (OER) which is vital for the anode (Ju et al., 2015).

3.1. Metal based electrodes

Metal based electrodes consist of metal oxides like MnO_2 and spinel, such as nickel cobaltite ($NiCo_2O_4$) known for their catalytic efficiency and stability (Song et al., 2014). Recent progress has led to the development of composite materials like Ni Mo and Ni Fe layered hydroxides (LDHs) which significantly boost surface area and catalytic performance of electrodes (Farhan, 2024). Oxygen evolution reaction (OER) makes those the promising options for efficient alkaline water electrolysis (Ďurovič et al., 2021).

Selecting the materials is essential for maximizing the performance and durability of electrolysis systems, which directly impacts the economic feasibility of producing green hydrogen. Understanding the characteristics and effectiveness of materials is key to creating electrolysis cells that are more efficient and environmentally friendly. Recent progress has introduced nanostructured and composite materials that significantly enhance the surface area and catalytic performance of electrodes. Examples of these materials are Ni Mo and Ni Fe layered hydroxides (LDHs) known for their improved hydrogen evolution reaction (HER) and oxygen evolution reaction (OER) capabilities (Benghanem et al., 2023; El-Shafie et al., 2019). Choosing materials is crucial for optimizing the effectiveness and durability of alkaline water electrolysis systems thus influencing the feasibility of green hydrogen production (Anwar et al., 2021; Huang et al., 2024). Nickel (Ni) and iron (Fe) play a role in facilitating electrochemical reactions for hydrogen generation in alkaline water electrolysis (Bespalko and Mizeraczyk, 2022; Pérez-Alonso et al., 2014). Nickel is commonly used as a cathode material due to its activity while iron finds applications in various electrode setups, including anodes and cathodes (Liu et al., 2020; Suen et al., 2017). The characteristics and advantages of electrodes are presented in Table 1.

Metals when used alone or in combinations like nickel iron (Ni Fe) alloys show properties for both the hydrogen evolution reaction (HER) and oxygen evolution reaction (OER) which are steps in electrolysis processes (Zhao et al., 2024). Nickel based electrodes are valued for their conductivity and resistance to corrosion making them suitable for long term electrolysis operations (Wang et al., 2024). On the other hand, iron-based electrodes provide cost options while still delivering reasonable electro catalytic performance (Chen et al., 2015). Using alloys like Ni Fe improves the durability and efficiency of electrodes by combining both metals' characteristics (Zhao et al., 2024). These metal-based electrodes play a role in enhancing the performance and lifespan of alkaline water electrolysis systems making them vital components in hydrogen production technologies (Esfandiari et al., 2024). Hence the development of electrocatalysts for water electrolysis is a growing field with importance to the community (Walke and Sathe, 2012). Table 2 shows the comparison of electricity consumption, conductivity and resistance to corrosion for different electrodes.

3.1.1. Efficiency

Nickel is commonly employed as a material because of its level of efficiency (Schalenbach et al., 2018; Zhang et al., 2018). Studies have shown that nickel electrodes can achieve an energy efficiency of around 60–70% at a current density of 500 mA/cm^2. Cobalt-based electrodes can achieve a slightly higher efficiency (Abbas et al., 2023), the percentage typically falls between 65 and 75 under circumstances based on the catalyst utilized. Stainless steel proves to be a choice of material (Brisse et al., 2018), However it is often less efficient, at around 50 to 60%.

3.1.2. Performance

Hydrogen production rates are generally favourable, with nickel electrodes yielding 0.9–1.1 L/h of hydrogen per cm^2 of area at 500 mA/cm^2. Iron electrodes show efficiency with outputs around 0.7 to 0.9 L/h per cm^2 at the same current density due to their higher potential (Selembo et al., 2010)

3.1.3. Durability and lifespan

Nickel electrodes, in alkaline electrolyzers usually last between 5 to 10 years based on how they are used (Davies, 2012; Selembo et al., 2010). The lifespan of these electrodes might be alike. They need upkeep because of passivation and possible pitting (Akpanyung and Loto, 2019; Frankel, 1998). The lifespan of cobalt electrodes can be extended up to 10–12 years because they have durability, against wear and corrosion compared to other options. However, they are more expensive (Kurzweil and Garche, 2017).

Table 1. Characteristics, advantages of electrodes.

Category	Material	Characteristics	Advantages	References
Metal-based electrodes	MnO_2, $NiCo_2O_4$, Ni Mo, Ni Fe LDHs	High catalytic efficiency, stability, improved OER and HER capabilities	Enhanced surface area, long-term stability, cost-effective, improved durability and efficiency	Gledhill et al., 2005; Kim et al. 2011; Jiang et al., 2012; Yan et al., 2017
Non-metal electrodes	Carbon cloth, carbon felt, CNTs	High conductivity, chemical stability, corrosion resistance	Customizable surface area, enhanced performance for hydrogen production, promising OER and HER activity	Wang et al., 2012; Balach et al., 2018; Zhou et al., 2020
Composite and nano-structured electrodes	Ni Fe LDHs, CNT supported catalysts, ZnO nanowires, Pt nanoparticles	High activity, enhanced conductivity, durability	Boosted electrolysis efficiency, cost-effective, eco-friendly, enhanced reaction rates and catalyst durability	Cui and Meng, 2020; Rezaei and Irannejad, 2022

Table 2. Comparison of electricity consumption, conductivity and resistance to corrosion for different electrodes.

Parameter	Nickel-based Electrodes	Stainless Steel Electrodes	Cobalt-based Electrodes	Copper-based Electrodes	References
Electricity Consumption	4.5–5.5 kWh/Nm^3	5.5–6.5 kWh/Nm^3	4.0–4.8 kWh/Nm^3	Not typically used due to corrosion issues	Marčeta Kaninski et al., 2006
Conductivity	14.3 × 106 S/m	1.4 × 106 S/m	Moderate (specific value not provided)	59.6 × 106 S/m	Frankel, 1998; Akpanyung and Loto, 2019
Resistance to Corrosion	0.1–0.3 mm/year	0.1–0.3 mm/year, may degrade with chlorides	$<$ 0.1 mm/year, better in aggressive conditions	High susceptibility to corrosion	Davies, 2012; Zhang et al., 2018
Activation Overpotential for the evolution of hydrogen	−0.32 V	−0.42 V	−0.35 V	−0.50 V	Heard and Lennox, 2020
Activation Overpotential for the evolution of oxygen	+0.61 V	+0.28 V	+0.39 V	+0.58 V	Heard and Lennox, 2020

3.1.4. Analysis of key parameters

The density of current plays a role, in determining how much hydrogen is produced per unit area on the surface and has a direct impact, on the rate of hydrogen production. Increasing the density typically results in hydrogen generation. However, it requires materials capable of withstanding these conditions without deteriorating over time (Akpanyung and Loto, 2019). High over potential and kinetic limitations are significant challenges associated with the hydrogen evolution reaction (HER) (Qadeer et al., 2024). In our analysis we delve into the potentials detected in fresh catalysts and electrode pairs showcasing how recent progress has lessened these potentials and improved the efficiency of producing hydrogen. The paper explores instances where novel electrode substances, like nickel alloys and blended catalysts have notably decreased over potential when compared to materials paving the way for a greener and economical approach, to generating hydrogen.

3.2. Non-metal based electrodes

Carbon based electrodes, such as materials like carbon cloth carbon felt and carbon nanotubes are known for their conductivity, stability against chemicals and resistance to corrosion (Wang et al., 2024). These materials have surface areas that can be customized with catalysts to improve their performance thereby contributing to efficient hydrogen production (Xu et al. 2023).

Graphene is a layer of carbon atoms arranged in a pattern that has attracted considerable interest due to its outstanding electrical conductivity and strong mechanical properties. Electrodes based on graphene exhibit promising activity in both HER and OER processes showing potential for enhancing electrolysis efficiency (Chen et al., 2019; Mbayachi et al., 2021). Additionally, non-metallic options like polymers such as polyaniline and Polypyrrole also display characteristics for electrolysis applications (Aydin and Köleli, 2006; Sharafinia and Rashidi, 2022).

Exploring metallic electrodes broadens the array of materials accessible for alkaline water electrolysis. This exploration creates opportunities to optimize performance, reduce expenses and improve sustainability in hydrogen production technologies (Zeng and Zhang, 2010).

3.3. Composite and nano-structured electrodes

Composite and nanostructured electrodes represent methods in alkaline water electrolysis that offer advantages for hydrogen production. These electrodes are made up of a mix of materials to boost their activity, conductivity and longevity (Zeng and Zhang, 2010; Zhang et al. 2021). For instance, nickel iron (Ni Fe) layered hydroxide (LDH) composites demonstrate performance in the oxygen evolution reaction (OER) because of the combined effects of nickel and iron species (Xu et al., 2022). For instance, some catalysts boost the speed of the oxygen evolution process (called OER) decreasing the energy required for OER without impacting the hydrogen evolution reaction (HER) directly. Likewise, carbon-based composites like carbon nanotube (CNT) supported catalysts show hydrogen evolution reaction (HER) performance and durability (Xu et al., 2022; Riaz et al., 2024).

Nanostructured electrodes, which include nanostructured metal oxides and catalysts provide surface areas and unique shapes that enhance reactions effectively. Zinc oxide (ZnO) nanowires, for example, have OER capabilities and strength in alkaline conditions (Keles et al., 2024). Furthermore, nanostructured catalysts such as platinum (Pt) nanoparticles supported on carbon materials exhibit outstanding HER performance and resilience against catalyst degradation (Kameya et al., 2016). The electrical conductivity of electrode materials is crucial for efficient charge transfer. Highly conductive materials, such as metals (nickel, platinum, etc.), allow for rapid electron movement, reducing internal resistance and overpotential. In contrast, materials like ZnO with low electrical conductivity (e.g., 7.261×10^{-7} S/cm) are less efficient unless modified with conductive coatings or composites to improve their performance. Transition metal oxides (e.g., ZnO, NiO) and layered double hydroxides (LDHs) exhibit good catalytic activity for OER due to their favourable electron structures, which lower activation energy (Shawuti et al., 2014).

These composite and nanostructured electrodes play a role in enhancing the efficiency, cost effectiveness and sustainability of alkaline water electrolysis systems. This contributes significantly to the progress of eco hydrogen technologies.

4. CATALYSIS FOR ELECTROLYSIS

The importance of catalysts in alkaline water electrolysis cannot be overstated as they play a role in increasing the efficiency of electrolysis by reducing activation energy barriers and speeding up reactions. The oxygen evolution reaction (OER) at the anode leads to kinetics and decreased over potentials. For example, platinum (Pt) based catalysts are recognized for their activity in HER while nickel iron (Ni Fe) based catalysts exhibit outstanding performance in OER (Wang et al., 2021).

Catalysts do not enhance reaction rates. They contribute to electrode stability and longevity which are essential for sustained electrolysis operation. The development and optimization of catalyst materials and structures are pivotal in achieving friendly hydrogen production within alkaline water electrolysis systems (Sapountzi et al., 2017).

4.1. Transition metal catalysts

Transition metal catalysts, nickel (Ni) cobalt (Co) and their compounds play a role in alkaline water electrolysis by catalysing the oxygen evolution reaction (OER) at the anode. Nickel based catalysts like nickel iron (Ni Fe) alloys and nickel cobalt (Ni Co) oxides demonstrate activity and durability in alkaline conditions making them well suited for electrolysis (Han et al., 2016). Catalysts containing cobalt, such as cobalt oxide (Co_3O_4), show performance in Oxygen Evolution Reaction (OER) which enhances the efficiency of electrolysis processes. Evaluating these transition metal catalysts is essential for optimizing electrolysis systems and promoting hydrogen technologies (Han et al., 2016; Walke et al., 2017).

4.2. Noble metal catalysts

When it comes to metal catalysts, materials like platinum (Pt) and palladium (Pd) exhibit activity in both the Hydrogen Evolution Reaction (HER) and OER. However, their high cost and limited availability pose challenges. Palladium (Pd) shows potential for the OER due to its activity (Sarkar et al., 2018) and improved stability compared to platinum (Pt) in alkaline environments. Researchers are actively exploring metals and their alloys or composites to enhance efficient alkaline water electrolysis (Marini et al., 2012).

4.3. Non-metal catalysts

Non-metallic catalysts, including metal oxides and phosphides offer options for alkaline water electrolysis. Metal oxide catalysts like cobalt oxide (Co_3O_4) and manganese oxide (MnO_2) demonstrate activity during the Oxygen Evolution Reaction at the anode (Akbayrak and Önal, 2021). Phosphide based catalysts such as nickel phosphide (Ni2P) also show performance in the Hydrogen Evolution Reaction, at the cathode (Rekha et al., 2021). The catalysts that are not made of metal offer ways to improve the efficiency of electrolysis while cutting down on the expenses linked to using metal catalysts (Walke et al., 2023). Figure 2 shows metal oxide catalysts like cobalt oxide (Co_3O_4) and manganese oxide (MnO_2) electro catalyst for OER.

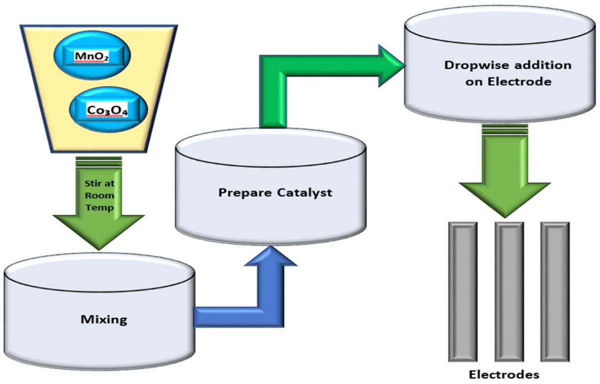

Figure 2. Metal oxide catalysts like cobalt oxide (Co_3O_4) and manganese oxide (MnO_2) electrocatalyst for OER.

4.4. Hybrid catalysts

Combining materials to create catalysts boosts performance in alkaline water electrolysis by taking advantage of the interactions between components. For example, pairing nickel iron layered hydroxides (NiFe LDH) with carbon nanotubes (CNTs) has demonstrated catalytic activity for the oxygen evolution reaction (OER) due to improved conductivity and active surface area (Gultom et al., 2021). Another instance involves integrating cobalt phosphide (CoP) with nitrogen doped graphene, which enhances the hydrogen evolution reaction (HER) by enhancing electron transport and stability (Liu and Li, 2016; Reith et al., 2021). These hybrid catalysts present an approach for enhancing the efficiency and longevity of electrolysis (Walke et al., 2023).

4.5. Catalyst performance metrics

Evaluating catalyst effectiveness in alkaline water electrolysis relies on metrics such as over potential which gauges a catalyst's efficiency by measuring the potential needed beyond equilibrium. Another important metric is the Tafel slope indicating both reaction kinetics and charge transfer efficiency. Stability and durability under conditions are also factors that influence a catalyst's long term performance (Chatenet et al., 2022). Furthermore, the turnover frequency (TOF) offers insights into the efficiency per active site while the electrochemical surface area (ECSA) evaluates the available surface area for reactions (Greeley et al., 2006).

5. METHODS OF ELECTRODE AND CATALYST EVALUATION

Methods for assessing electrodes and catalysts in alkaline water electrolysis involve a mix of electrochemical and physical characterization methods. Electrochemical techniques like voltammetry (CV) and linear sweep voltammetry (LSV) are utilized to gauge activity, over potential and Tafel slopes (Gouws, 2012).

5.1. Electrochemical characterization

The evaluation of electrodes and catalysts in alkaline water electrolysis heavily relies on characterization techniques. Cyclic voltammetry (CV) is commonly used to assess activity and stability by measuring response at varying potentials. Electrochemical impedance spectroscopy (EIS) aids in understanding charge transfer resistance and electrode kinetics through impedance analysis across frequencies (Mahmood et al., 2018). Tafel analysis offers insights into reaction kinetics and mechanisms by plotting over potential against the logarithm of density aiding in determining Tafel slope and exchange density (Suen et al., 2017). These combined techniques offer an understanding of the behaviour of electrodes and catalysts.

5.2. Physical characterization

Physical characterization techniques are vital for understanding the structural and morphological properties of electrodes and catalysts in alkaline water electrolysis. X-ray diffraction (XRD) is used to determine the crystalline structure and phase composition of materials, providing insights into their structural integrity and stability (Holder and Schaak, 2019). Scanning electron microscopy (SEM) offers detailed images of surface morphology, allowing the analysis of surface roughness, porosity, and particle size (Nasrollahzadeh et al., 2019). Surface area analysis, often performed using techniques like Brunauer-Emmett-Teller (BET) measurements, helps in evaluating the active surface area available for electrochemical reactions, which is crucial for catalyst performance (Baig et al., 2021).

5.3. Comparative studies

Comparative studies offer insights into the performance of electrodes and catalysts in alkaline water electrolysis. For example, the study of comparing materials, such as nickel based, and iron-based catalysts was conducted by (Suen et al., 2017). They found that nickel iron layered double hydroxides (NiFe LDHs) outperformed materials in the oxygen evolution reaction (OER). Another study by [55]McCrory et al. (2013) evaluated electrocatalysts for OER emphasizing the effectiveness of mixed metal oxides and identifying factors influencing their performance. Another study was conducted by [5]Mahmood et al. (2018), in which they compared layered double hydroxides (LDHs) with perovskite oxides showcasing the enhanced stability and activity of LDHs in alkaline conditions. These comparative analyses aid in selecting the materials for efficient and long-lasting water electrolysi1s. Nickel and iron layered double hydroxides (NiFe LDHS) show performance in enabling the oxygen evolution reaction compared to nickel based materials because of the combined impact of nickel and iron that boosts catalytic activity. Introducing iron into the nickel framework promotes the creation of sites and refines the electron structure to enhance oxygen evolution kinetics. Moreover, added benefits come from the arrangement of NiFe LDHS for OER which offers a surface area that boosts access to active sites.

6. CHALLENGES AND FUTURE PROSPECTIVES

Future perspectives in catalyst development for alkaline water electrolysis revolve around enhancing material efficiency and stability during operation. A significant challenge is the over potential required for the oxygen evolution reaction (OER) which hampers system efficiency. One of the challenges lies in the durability of catalysts over time as many materials degrade or lose effectiveness leading to replacement or upkeep (McCrory et al., 2013). Moreover, the cost and scalability issues associated with premium noble metal catalysts create significant economic obstacles for large scale hydrogen production (Lakkimsetty et al., 2020). It is essential to address these hurdles to advance hydrogen production technologies. Looking ahead a crucial aspect involves the development of materials like hybrid- and nano- catalysts to boost performance while cutting down costs.

6.1. Research trends

Research trends are currently centered on enhancing performance and cost effectiveness in catalyst research for alkaline water electrolysis. Recent developments include perovskite oxides known for their activity and stability in the oxygen evolution reaction (OER) (Seitz et al., 2016). Hybrid catalysts that combine materials such as transition metal oxides and hydroxides show promise in enhancing efficiency and longevity. Nano structuring materials are also gaining traction as they increase the surface area and improve electro-chemical properties (Zhang et al., 2014). Advancements in catalysts like metal frameworks (MOFs) and carbon-based materials are gathering attention for their potential to reduce costs and promote environmental sustainability (Al Bulushi et al., 2022).

6.2. Future directions

Future avenues open in the study of electrodes and catalysts for alkaline water electrolysis prospects and research possibilities. A key focus area involves the creation of catalysts efficiently facilitating both the hydrogen evolution reaction (HER) and oxygen evolution reaction (OER) thereby streamlining system complexity and expenses (Hoang et al., 2023). Furthermore, efforts are underway to develop single atom catalysts renowned for their heightened activity and stability owing to optimized atom usage and distinctive electronic characteristics. The integration of intelligence and machine learning techniques to enhance catalyst design and performance predictions is also a burgeoning field of interest (Kitchin, 2018). Exploring available materials such as earth abundant metals and carbon-based nanomaterials represent another crucial avenue for research (Walke et al., 2024).

6.2.1. Prototyping and scaling up technologies

Prototyping and upscaling efforts in alkaline water electrolysis technologies play a role in transitioning from laboratory experimentation to implementation (Saba et al., 2018). These initiatives involve creating pilot scale systems that mimic the effectiveness and efficiency of lab setups while tackling issues related to durability and affordability (Arthur et al., 2011). Scaling up also requires refining manufacturing processes to make quantities of high-quality electrodes and catalysts consistently. Furthermore, partnerships with industries and funding programs play a role in speeding up the commercialization of these technologies ensuring their practicality and sustainability on a scale (Zhao et al., 2023).

6.2.2. Integrating advanced manufacturing techniques

Integrating manufacturing techniques is essential for enhancing the efficiency and scalability of alkaline water electrolysis systems. Methods like manufacturing (3D printing) and automated assembly can cut down production costs significantly and improve the accuracy of electrode and catalyst structures (Yang et al., 2018). These methods allow for designs with optimized surface areas enhancing performance. Streamlined procedures such as roll to roll processing can assist in mass producing components making green hydrogen technology economically feasible. By harnessing these techniques, the shift from small scale laboratory research to use can be accelerated (Eichman et al., 2014).

6.2.3. Exploring new electrode and catalyst configurations

It is crucial to investigate configurations of electrodes and catalysts to improve the efficiency and longevity of alkaline water electrolysis systems (Arthur et al., 2011). Unique designs, like nanostructured and hierarchical electrodes can increase surface area and enhance activity. Moreover, bifunctional catalysts that blend materials can boost performance for the hydrogen evolution reaction (HER) and oxygen evolution reaction (OER) (Mehta and Cooper, 2003). Studies on three architectures also hold promise in optimizing mass transport and reducing over potentials. These advancements could enhance the viability and operational effectiveness of hydrogen production technologies (Sathre et al., 2014).

7. CONCLUSIONS

This analysis has focused on the importance of decision making and evaluating catalysts in producing hydrogen through alkaline water electrolysis. The use of metal electrodes containing nickel and iron and their combinations has demonstrated promise because of their performance and longevity. Nonmetallic electrodes such as those made from carbon based materials provide alternatives that offer both conductivity and stability. Composite and nanostructured electrodes present options, by enhancing surface areas and electrochemical properties to improve efficiency.

Catalysts are important for enhancing the efficiency of alkaline water electrolysis processes. Nickel and cobalt compounds are commonly used as transition metal catalysts due to their effectiveness in reactions. Although noble metal catalysts come with a price tag, products made from them offer both reactivity and stability. Non-metallic and mixed catalysts are becoming popular as eco-options. Evaluating these materials includes procedures, like testing their performance characterizing their properties and assessing their durability and stability over time.

Although advancements have been made in the field of hydrogen production technology and its efficiency, improvements to reduce costs and enhance long term durability still pose challenges. Future research efforts will focus around the utilization of atom catalysts, with the aid of machine learning for optimization purposes as well as exploration of new materials. These avenues hold promise for moving the field and enhancing both the effectiveness and economic feasibility of hydrogen production.

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