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Exploring Metal Oxides Nanostructures for Sustainable Hydrogen Evolution via Indoor Electrocatalytic Water Splitting

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Abstract

Review Article

The widespread adoption of green hydrogen production plays a pivotal role in establishing a sustainable circular economy. A major challenge lies in the efficient production of hydrogen to meet the demands of commercial scale applications. Hydrogen production through water electrolysis is an effective method to utilize surplus renewable energy efficiently, offering advantages in energy conversion and storage, where catalysis or electrocatalysis plays a pivotal role. The development of active, cost effective, and stable catalysts or electrocatalysts is a critical prerequisite for efficient electrocatalytic hydrogen production from water splitting for practical applications, which is primary focus of this review. On the one hand, precious metals are commonly utilized to investigate the two half-cell reactions namely the HER and OER. However, the use of precious metals such as Au, Ag, Pt, Ru, as electrocatalysts, is limited by their cost and less availability, hindering their practical application. In contrast, non-precious metal-based electrocatalysts are abundant, environmentally friendly, and low-cost, which demonstrating high electrical conductivity and electrocatalytic performance comparable to noble metals. Thus, these electrocatalysts have the potential to replace precious metals in the water electrolysis process. In this review, we present key fundamental insights into water electrolysis, which not only enables higher hydrogen production but is also cost-effective.

Keywords: Green Hydrogen, Water Electrolysis, Electrocatalysis, Non-precious Metal Catalysts, Sustainable Circular Economy.

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1. INTRODUCTION

1.1 Nanoscience and Nanotechnology

The study of materials and technologies at the nanoscale, which typically ranges from one to one hundred nanometers, is the focus of the rapidly developing fields of nanoscience and nanotechnology. Materials display special qualities that distinguish them from their bulk counterparts at this scale, making them desirable for a variety of applications [1]. Nanotechnology deals with the design, creation, and manipulation of materials and devices at this scale, whereas nanoscience studies the characteristics and behavior of materials at the nanoscale. The creation of novel materials with unique properties is one of nanotechnology's most important application. For instance, it is possible to make nanomaterials stronger, lighter, and more resilient than their bulk equivalents, which makes them perfect for use in healthcare, energy storage, and electronics applications [2].

Additionally, the special qualities of nanoparticles can be used to transport drugs, where they can be made to target particular cells or tissues, enhancing therapeutic efficacy while reducing adverse effects. The creation of nanoelectronics, in which components and devices are created at the nanoscale, is another significant use of nanotechnology. As a result, computers have become quicker and more potent, with lower and energy-saving component sizes. Nanosensors that can detect extremely minute concentrations of chemicals or biological agents, which can be utilized for environmental monitoring, medical diagnostics, and

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other purposes, have been made possible by nanoelectronics. With the creation of novel materials and technologies that can convert, store, and consume energy more effectively, nanotechnology has also contributed significantly to the advancements in the realm of energy. For instance, the creation of more effective solar cells with better energy conversion rates and cheaper costs is a result of nanotechnology [3]. High-capacity batteries and supercapacitors, which are essential for the development of electric vehicles and renewable energy systems, have also been made possible by nanotechnology.

A safe and adaptable energy source, hydrogen may be utilized for anything from power generation to transportation. Water splitting, a procedure that employs electricity to divide water molecules into their parts of hydrogen and oxygen, is one possible way to produce hydrogen. A green and sustainable hydrogen fuel source can be produced using this technology plus renewable electrical sources, such as solar or wind energy. The effectiveness and scalability of water-splitting technologies are also continuously being improved through materials science and engineering developments, making them more suitable for large-scale industrial applications. Hydrogen production by water splitting has the potential to significantly aid in the shift to a low-carbon economy with more research and funding.

Aluminum nanoparticles (AlNPs), show potential as hydrogen and water-splitting catalysts. AlNPs are an appealing substitute for traditional catalysts like platinum because of their special qualities, including their high surface area, high reactivity, and inexpensive cost. AlNPs can be utilized as a catalyst for the electrochemical or photoelectrochemical splitting of water to create hydrogen gas. AlNPs are used as an anode catalyst in electrochemical water splitting, where they encourage the oxidation of water to produce oxygen gas and protons. AlNPs can be utilized as a co-catalyst with a semiconductor in photoelectrochemical water splitting to increase the effectiveness of hydrogen synthesis. Al NPs can be utilized to create bimetallic catalysts with improved catalytic activity for hydrogen evolution by combining them with other metal catalysts like cobalt and nickel. AlNPs have been employed in numerous energy-related applications, including fuel cells, solar cells, and supercapacitors, in addition to their function in the water-splitting process [4]. AlNPs are a promising material for increasing effectiveness and lowering the cost of hydrogen generation, which is a crucial step in the transition to a sustainable energy economy.

2. The Role of Metallic Electrocatalysts

Water electrolysis is a promising technique for producing hydrogen that can be used as a clean fuel in a variety of applications. The electrocatalysts employed affect the efficiency and effectiveness of the water-splitting reaction. Platinum, nickel, and cobalt are examples of metallic electrocatalysts that are crucial to this process because they lower the energy barrier needed for the electrochemical processes to take place. These electrocatalysts assist in the splitting of water molecules into oxygen and hydrogen by promoting the exchange of electrons [5]. Platinum is a very effective electrocatalyst, but because of its high cost, it cannot be used to produce hydrogen on a big scale.

Electrocatalysts made of nickel and cobalt, which are less expensive and more accessible, are better suited for this use. The performance and stability of water electrolysis can be improved by using novel, effective, and affordable electrocatalysts to produce hydrogen sustainably. Moreover, iron and aluminum can also potentially serve as electrocatalysts for hydrogen evolution reaction (HER) but they have lower activity and stability due to the oxides layer formed on their surface, which restricts them to react with water [6]. However, many researchers showed up with several techniques to improve these metals' electrocatalytic effectiveness, including alloying with other metals, altering their surface structure, and using composite materials.

2.1. Nickel and Its Salts

Nickel is a metallic element with the chemical symbol Ni and atomic number 28. It has a silvery-white lustrous appearance, with a slight golden tinge. Nickel has a face-centered cubic lattice, which means that each atom is positioned at the corner and in the middle of each face of the cube in a regular pattern as shown in Figure 1. Nickel is one of the most abundant elements on Earth, occurring primarily in the Earth's crust and core. Nickel is a hard and ductile metal, with a high melting point and good corrosion resistance. The capacity of nickel to adsorb hydrogen atoms onto its surface, which generates hydrogen gas, is one of the reasons that it is an effective electrocatalyst for HER [7]. However, nickel's tendency for surface oxidation and corrosion, which can lower its catalytic activity, is one of the main issues with employing nickel as an electrocatalyst. The two powder salts of nickel can also use for water-splitting through electrolysis because they are cheap in price and easy to use and they are soluble in water while pure nickel does not.

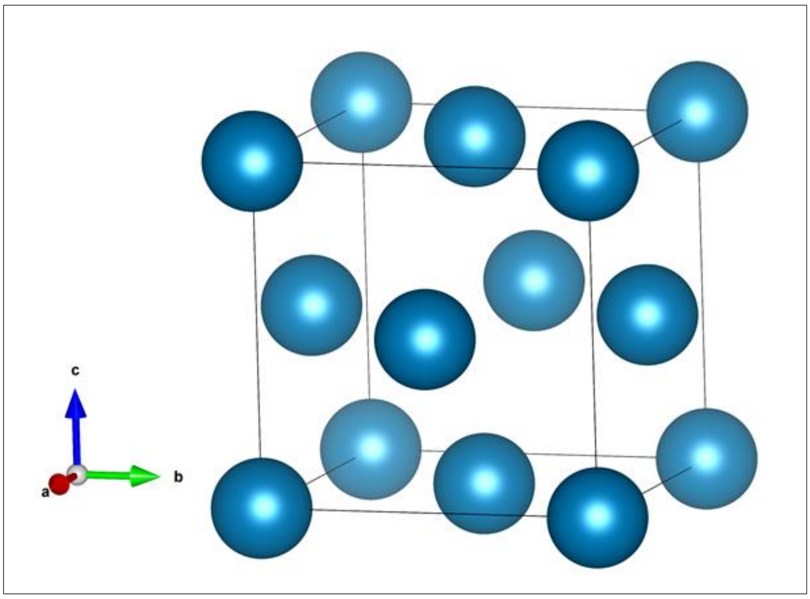

Figure 1: Crystal structure of Nickel

Chemical substances that include nickel in its +2-oxidation state are referred to as nickel two salts, sometimes known as nickelous salts. These salts form when an anion, such as chloride(Cl^-), sulphate (SO_4^{2-}), or nitrate (NO_3^-), bonds with a nickel cation (Ni^{2+}). Nickel sulfate (NiSO_4), nickel chloride(NiCl_2), and nickel nitrate $\mathrm{Ni(NO_3)_2}$ are among the common nickel salts. These salts serve various purposes in industrial processes and laboratory experiments. The specific properties of nickel depend on the particular salt. For instance, nickel chloride is a yellow-green crystalline solid that also dissolves in water, while nickel sulphate is a blue crystalline solid [8]. These salts are used for electroplating, as electrocatalysts, and as sources of nickel ions in chemical processes, among other experiments.

Overall, previous research indicates that both nickel nitrate hexahydrate and nickel chloride hexahydrate can be efficient electrocatalysts for the HER in water splitting, although the selection of one over the other may depend on particular circumstances and the needs of the process.

2.2. Cobalt and Its Salts

Cobalt is a transition metal with an atomic number of 27 and the scientific symbol Co, it belongs to Group 9 of the periodic table. At room temperature and pressure, cobalt exhibits a face-centered cubic (FCC), under high pressure, can transform and adopt a hexagonal close-packed (HCP) crystal structure as shown in Figure 2. Cobalt is a ferromagnetic material, which means that it retains a magnetic field even when no magnetic field is present [9]. The magnetic properties of cobalt are due to the alignment of electron spin and due to the 27 protons present in its nucleus. Cobalt is employed in a wide range of industrial processes due to its distinct magnetic characteristics, including the creation of magnetic alloys and rechargeable batteries.

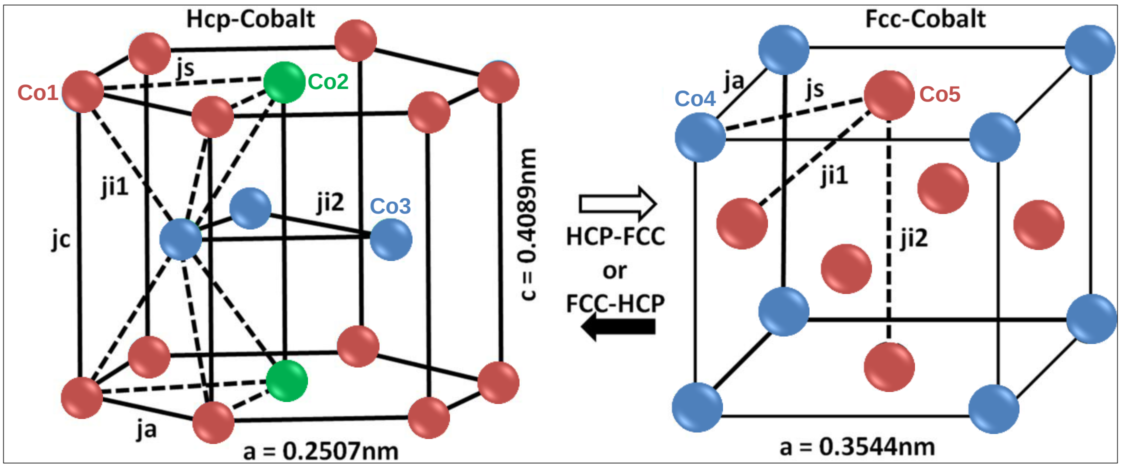

Figure 2: HCP and FCC crystal structure of Cobalt

An interesting use of cobalt is as an electrocatalyst to produce hydrogen. It is a possible method for producing clean, renewable fuels is the electrolysis of water. This procedure is not economically feasible due to the significant energy input required. The energy needed for this process may be greatly reduced using electrocatalysts, making it more practical for producing hydrogen on a wide scale. Cobalt-based electrocatalysts are appealing due to their strong catalytic activity for the hydrogen evolution process (HER) and comparatively inexpensive price, cobalt-based electrocatalysts are appealing. Cobalt salts such as cobalt phosphate, sulfide, and cobalt nitride have been thoroughly investigated for their potential application as HER electrocatalysts. It has excellent catalytic activity, great stability, and good selectivity for hydrogen generation have all been discovered in these materials. For instance, it has been demonstrated that cobalt phosphate, which has a low overpotential and strong long-term stability, is a very active and stable electrocatalyst for HER. Cobalt sulfide and cobalt nitride have also been shown to be efficient electrocatalysts, with comparable or even better performance than cobalt phosphate [10]. Additionally, cobalt-based materials can be synthesized easily using simple and scalable methods, making them attractive for industrial applications [11].

2.3. Aluminum as an Electrocatalyst

Aluminum has the chemical symbol Al and the atomic number 13. It is a component of the periodic table's boron group, which also includes the elements boron (B), gallium (Ga), indium (In), and thallium (Tl). Aluminum is a common element in the Earth's crust, accounting for approximately 8% of the total by weight. It belongs to Group 13, referred to as the "scandium group" and is categorized as a post-transition metal. Aluminum is a lightweight, silvery-white metal that is widely utilized in a variety of sectors due to its unique qualities such as high strength-to-weight ratio, corrosion resistance, and strong thermal and electrical conductivity. Aluminum has a face-centered cubic (FCC) crystal structure, which means that each atom is surrounded by 12 nearby atoms at each cube's corners, plus a further atom in the center of each face [12].

This configuration enables the atoms to be packed closely together, producing a high density and robust metallic bonding. The process in which pure aluminum is reacted with water yields alumina and hydrogen while also releasing a significant quantity of heat [13]. The energy required for the reaction is provided by aluminum, which serves as a fuel or energy carrier.

The oxide layer on the aluminum surface prevents it to react with water, many techniques have been used for the removal of the oxide layer from aluminum's surface because it is an excellent catalyst for hydrogen production. these methods include chemical etching, mechanical methods, electrolytic methods and plasma cleaning methods. After the aluminum oxide layer has been removed, the pure aluminum may combine with water to create hydrogen, which can then be compressed and kept for later use or burnt to generate more heat. The reaction yields high-grade alumina, which is safe and may be recycled into aluminum or utilized in other technical processes. Overall, aluminum is an important component of this sustainable and efficient technique of hydrogen generation, which has the potential to fulfill the growing need for clean energy sources [14].

A possible technique for producing sustainable energy is the electrolysis of aluminum to produce hydrogen. Aluminum reacts with a strong base in water, creating aluminum hydroxide and hydrogen gas as a byproduct. Aluminum atoms lose electrons at the anode during the electrolysis process, creating aluminum ions that combine with water to produce aluminum hydroxide and hydrogen gas at the cathode. This method can potentially generate hydrogen at a cheap cost and with great efficiency, making it a competitive alternative to conventional fossil fuels. In addition, the waste product of aluminum hydroxide may be recycled and used once again in the manufacture of aluminum which will enhance its sustainability [15].

2.4. Iron as an Electrocatalyst

Iron has the symbol Fe and the atomic number 26. It is the fourth most prevalent element in the Earth's crust and the most widely utilized metal. Its significance stems from its unique features such as strength, durability, and adaptability [11]. Iron is characterized by a unique crystal structure known as body-centered cubic (BCC). Each iron atom is positioned in the center of a cube, with eight neighboring atoms positioned at the corners of adjacent cubes as shown in Figure 3. This BCC structure gives iron unique mechanical and physical characteristics including strength, ductility, and magnetic properties. Iron undergoes a phase change to a face-centered cubic (FCC) structure at temperatures over 912°C. The iron atoms are closely packed together in this configuration, which increases density but decreases ductility. Iron has been found as a viable electrocatalyst for the evolution of hydrogen by water electrolysis. Iron's electrocatalytic activity results from its capacity to speed up the crucial process of hydrogen evolution in water electrolysis [8].

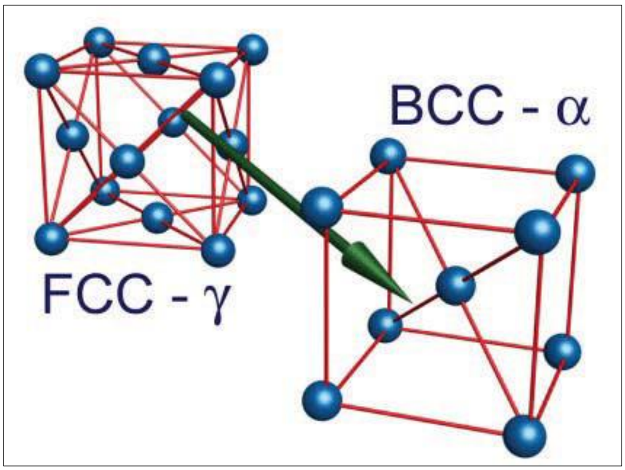

Figure 3: FCC and BCC crystal structure of Iron [16]

Iron's crystal structure is a crucial factor in determining its characteristics and behavior under various situations, and it is a crucial factor in many applications, including metallurgy and materials science. It is a necessary ingredient for the growth of red blood cells and the transportation of oxygen throughout the body, making it vital for many living things, including human beings. Iron-based electrocatalysts offer various advantages, including low cost, abundance, and environmental friendliness. In addition to being a good conductor of electricity, iron is also very stable in acidic and alkaline environments, which are common for the development of hydrogen. The effectiveness and stability of iron-based electrocatalysts have been improved via the use of diverse synthesis techniques and modifications. For instance, improving the surface chemistry of iron-based electrocatalysts or doping them with other metals might increase their stability and activity. Doping iron with transition metals like cobalt, nickel, and manganese, can improve its electrocatalytic activity by boosting its catalytic activity towards the hydrogen evolution process. Overall, iron-based electrocatalysts have excellent promise for the industrial production of hydrogen by water electrolysis, which is an exciting prospect for the generation of sustainable energy [17].

3. The Combined Effect of Ni-Al-Co-Fe

During electrolysis, water is reduced to generate hydrogen gas via the hydrogen evolution reaction (HER). Catalysts are necessary to improve efficiency and to lower the cost of this process. The mixture of aluminum, nickel, cobalt, and iron shows promising results. While nickel and cobalt are well-known HER catalysts, their high cost and low stability have limited their practical usage [18]. Therefore, in this experiment the salts of nickel and cobalt are used instead of pure nickel and pure cobalt because hydrated salts of nickel and cobalt react directly with water. Iron and aluminum have been discovered to improve the stability and activity of the catalyst system. Iron stabilizes the catalyst and prevents the development of inactive surface species, while aluminum's strong affinity for oxygen encourages the production of an oxide layer that shields the catalyst from corrosion and increases its toughness [13]. The previous research on the catalyst's composition has revealed that the ideal composition is influenced by the electrode's pH. Higher nickel concentration enhances performance at acidic pH levels, whereas higher cobalt content enhances performance at neutral pH levels.

Additionally, the catalytic activity of the catalyst has been discovered to be improved by the application of nanomaterials. More active sites for the HER reaction are provided by the nanoparticles' enhanced surface area. The Ni-Al-Co-Fe catalyst is a potential for HER in electrolysis due to its overall synergistic effects, exhibiting improved activity and stability. The broad use of hydrogen as a sustainable energy source requires the development of effective and affordable catalysts. The recombined effect increases its electrocatalytic activity for HER if its surface roughness increases. If the surface roughness of aluminum increases by itching its oxides layer from the upper surface it will react with water and prove to be a very powerful catalyst for hydrogen production and water splitting. The itching process is done in this experiment by using the 1 M electrolyte solution of NaOH and KOH. When the aluminum powder is dipped into the electrolyte solution of NaOH and KOH in an electrolysis setup the surface oxide layer of aluminum will be dissolved into the solution, and it will start performing its reaction for hydrogen production. The other metals nickel, cobalt, and iron will become electrochemically active in this electrolytic solution [19]. When iron, nickel, and cobalt powders are electrolyzed in the presence of a 1 M NaOH and KOH solution to produce hydrogen, the following reactions occur:

I. Nickel:
Cathode reaction: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$
Anode reaction: $2OH^- \rightarrow 1/2O_2 + H_2O + 2e^-$
Overall reaction: $2H_2O \rightarrow 2H_2 + O_2$

Nickel does not typically react with hydroxide ions and acts more inert in alkaline solutions. But nickel is a frequently used material for alkaline electrolysis electrodes, due to its excellent electrocatalyst properties.

II. Iron:

Cathode reaction: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$

Anode reaction: $Fe + 2OH^- \rightarrow FeO(OH) + H_2O + 2e^-$

Overall reaction: $Fe + 2H_2O \rightarrow FeO(OH) + H_2$

Hydroxide ions (OH^-) in the solution will react with iron to form iron oxide (Fe_2O_3) and hydrogen gas (H_2).

III. Cobalt:

Cathode reaction: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$

Anode reaction: $Co + 2OH^- \rightarrow CoO + H_2O + 2e^-$

Overall reaction: $Co + 2H_2O \rightarrow CoO + H_2$

Hydrogen gas and cobalt oxide (CoO) are the products of cobalt's reaction with hydroxide ions in the solution.

IV. Aluminum:

Cathode reaction: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$

Anode reaction: $2Al + 6OH^- \rightarrow 2Al(OH)_3 + 6e^-$

Overall reaction: $2Al + 6H_2O \rightarrow 2Al(OH)_3 + 3H_2$

Aluminum is a highly reactive metal that easily forms aluminum oxide (Al_2O_3) and H_2 when it comes into contact with hydroxide ions.

4. Introduction to Hydrogen as a Fuel and an Energy Carrier

Hydrogen is the first element of the periodic table and is represented as H_2. It is the most common element in the periodic table and a chemical element that is abundant throughout the universe. It is a highly combustible gas that has no flavor, smell, or color. Hydrogen has several uses, making it a necessary component in a variety of industries. The creation of ammonia for fertilizer is one of the major applications of hydrogen [20]. Additionally, it plays a crucial role in manufacturing methanol, a fuel utilized in many different sectors. The use of hydrogen as a motor fuel is another significant use. The application and generation of hydrogen is depicted in Figure 4.

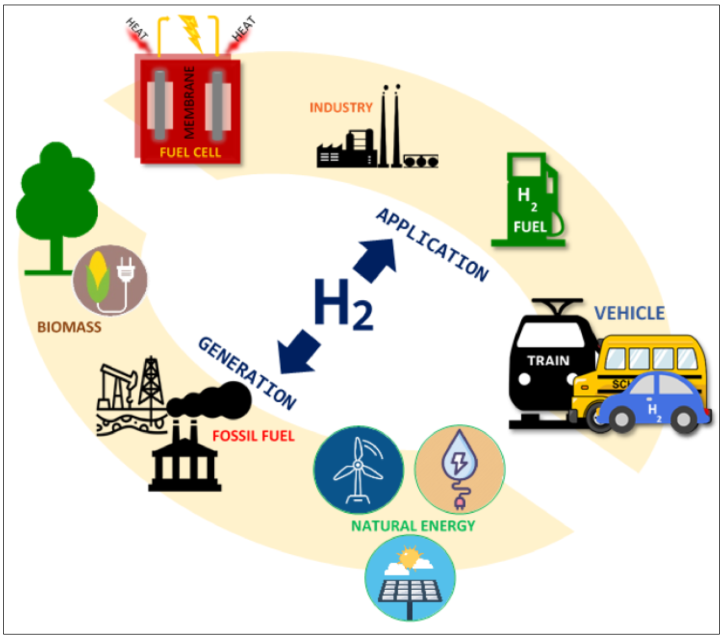

Figure 4: Hydrogen as an energy carrier [21]

There are some methods used for hydrogen production such as electrolysis, steam methane reforming, partial oxidation, and biomass gasification are also used for hydrogen production. In electrolysis, water is split into ions to produce hydrogen and oxygen using electricity. In the process of steam methane reforming, methane and steam react to create hydrogen and carbon dioxide. Steam methane has some disadvantages such as emissions of carbon dioxide from the process helping to cause climate change, it is a long-term, fossil fuel-based process that cannot be sustained and high temperatures and pressures are needed throughout the production process, which can be energy-intensive. Hydrocarbons are partially burned during partial oxidation resulting in hydrogen and carbon monoxide, and carbon monoxide is a toxic gas. The final step in biomass gasification is the gasification of organic material to create a hydrogen-rich gas stream. biomass gasification has disadvantages too such as the procedure might be difficult and specialized tools are needed, the availability of the feedstock might alter based on things like location and seasonal variations, and if the process is not adequately handled, it may emit some greenhouse gases [12]. Each approach has benefits as well as disadvantages in terms of effectiveness, expense, and environmental impact, and whether it is suitable for a given application will depend on the available resources. An appealing alternative to conventional combustion engines, hydrogen fuel cells create electricity by turning hydrogen into energy and only emit water and heat as waste products. Vehicles that run on hydrogen have the potential to drastically lower greenhouse gas emissions and enhance air quality. In the aerospace sector, hydrogen is also employed as a nuclear reactor coolant and as a fuel for rockets. The manufacturing of compounds like hydrogen peroxide and hydrochloric acid as well as the refinement of metals both require hydrogen as a reducing agent. Hydrogen is also being investigated as a potential source of energy storage [22].

When excess energy is produced from renewable sources such as wind or solar power, it can be stored by using electrolysis to split water molecules into hydrogen and oxygen. Therefore, storing the hydrogen and utilizing it to create energy as needed becomes possible, making it a reasonable replacement for conventional battery storage. Hydrogen has a variety of uses, but several obstacles need to be removed before it can be extensively used as an alternative fuel. The cost of production is one of the biggest obstacles. Most hydrogen is currently generated using fossil fuels, which are not long-term sustainable. The infrastructure for hydrogen fueling stations is also lacking, which makes it difficult for hydrogen-powered vehicles to gain broad adoption [23].

Overall, hydrogen is a versatile and useful element in many sectors due to its wide range of uses. Hydrogen is a key component of the global transition to a more sustainable future in terms of lowering greenhouse gas emissions and enhancing air quality. Hydrogen has the potential to contribute significantly to the global energy mix with further research and funding, but it will need to overcome several obstacles to fulfill its potential [24].

4.1. Hydrogen Production through Electrolysis

The technique of producing hydrogen using electrolysis involves using electricity to split water into hydrogen and oxygen. Due to its ability to make use of renewable energy sources, this technique has been recognized as a crucial component in the growth of a sustainable hydrogen production sector. An electrolyzer, a device with two electrodes (an anode and a cathode) and an electrolyte solution, is commonly used in the electrolysis process [5]. The water molecule splits into hydrogen and oxygen gas in the electrolyte solution when an electric current is applied to it. The hydroxide ions then go towards the anode, while the hydrogen ions move in the opposite direction. The hydrogen ions acquire electrons from the electrode at the cathode, which reduces them to hydrogen gas (H_2) as shown in Figure 5. The hydroxide ions provide their electrons to the electrode at the anode, where they then undergo oxidation to produce oxygen gas (O_2).

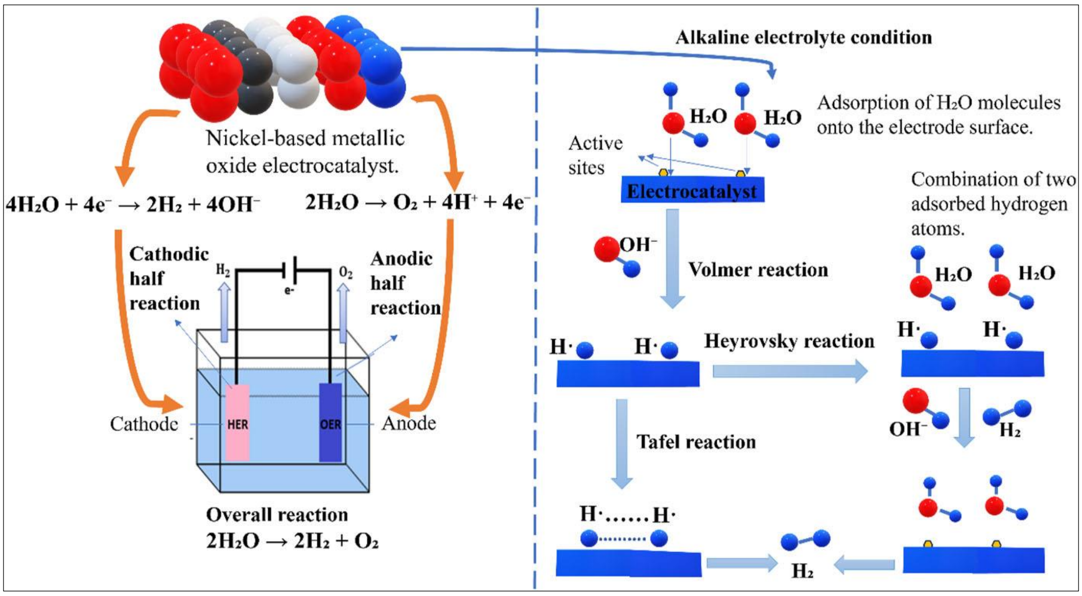

Figure 5: Insights of Electrolysis [25]

The external electrical power source provides the binding energy needed to break the molecular bonds holding the hydrogen and oxygen atoms together in the water molecule. Water splitting requires a certain amount of energy, which is determined by several variables including electrode material, voltage, electrolyte content, and cell design [26]. The chemical energy contained in the separated hydrogen and oxygen gases can be utilized for a variety of reasons, including fuel cells for electrical energy generation, combustion engines for transportation, and chemical processes for use in industry. The chemical energy trapped in the separated hydrogen and oxygen gases is released when they are mixed in a fuel cell, creating electrical energy and water as a byproduct [27].

This procedure is a potential clean energy generation method since it is very effective and emits no hazardous pollutants. The created hydrogen gas may then be collected and stored for later use in several activities, including power generation, fuel cells for electric cars, and industrial processes. Compared to more conventional techniques of producing hydrogen, including steam methane reforming, electrolysis has several benefits [28]. Firstly, the method is quite effective and has the potential for up to 80% conversion efficiency. Second, the procedure may be run on renewable energy sources like solar, wind, and hydropower, which will cut carbon emissions and aid in the transition to a future with sustainable energy. Thirdly, the electrolysis procedure is a clean and ecologically responsible way to manufacture hydrogen because it doesn't emit any greenhouse gases [10].

Despite its advantages, the widespread adoption of electrolysis-based hydrogen generation is not without its challenges. The high cost of power necessary for the electrolysis process, which now accounts for a significant portion of the entire cost of hydrogen generation, is one of the key obstacles. Additionally, there is a need for the creation of more advanced and economical electrolyzer technologies that may lower startup costs and boost process efficiency all around. Therefore, electrolysis is a process that has promise for producing clean and long-lasting hydrogen fuel. Even if there are obstacles to be addressed, ongoing technological improvements and the expansion of renewable energy sources are making the general adoption of electrolysis-based hydrogen generation more and more likely. This technology has the potential to be essential in the shift to a low-carbon economy and a more sustainable future. Water splitting is the process of dividing water into its hydrogen and oxygen components using a variety of techniques [29].

The process of electrolysis, which involves running an electric current through a solution of water and an electrolyte to separate the water's constituent ions, is often used. Utilizing catalysts, such as those manufactured from metal oxides or nanoparticles, is another way to split water. These catalysts can aid in accelerating the water-splitting reaction, increasing its effectiveness, and lowering its cost. Additionally, the generation of clean hydrogen fuel using renewable energy sources like solar, or wind power drives the water splitting process. Using specialized materials that can absorb sunlight and transform it into electrical energy, which is then utilized to drive the water-splitting reaction, this technique, known as photoelectrochemical water splitting [8]. As it enables the effective generation of hydrogen fuel using just water and renewable energy sources, water splitting has the potential to be an essential technology for creating clean, renewable energy. Advancements in research, leading to increased efficiency and efficacy of water-splitting systems, are expected to make this technology increasingly vital in the transition towards a more sustainable energy future.

5. Reduction Catalysts in Water Splitting

A water reduction catalyst is a chemical that aids in the conversion of water into hydrogen gas, which may be utilized as a clean and sustainable energy source. A reduction catalyst speeds up the HER (hydrogen evolution reaction) process by providing a surface for the reaction to occur and lowering the activation energy required for the reaction. Electrocatalysts provide active sites where water molecules can adsorb and undergo chemical transformations. At these sites, the water molecules are activated, and their chemical bonds are weakened, making it easier for them to react. During the water splitting process, two main reactions occur at the electrodes. At the cathode, protons are reduced to form hydrogen gas (H_2), while at the anode, water molecules are oxidized to produce oxygen gas (O_2) and protons. Electrocatalysts facilitate these reactions by lowering the energy barriers required for the reactions to proceed.

Water is converted to hydrogen gas in the HER process by the exchange of protons and electrons, but to get over the activation barrier and start the reaction, a certain quantity of energy is needed [28]. The interaction between the water molecules and the reduction catalyst, such as platinum or nickel, and cobalt encourages the creation of hydrogen atoms. The catalyst offers a different route for the reaction to take place with lower activation energy than the uncatalyzed process by adsorbing water molecules onto its surface. This speed up the reaction by making it easier for electrons and protons to move between the reactants and products. In addition, the stabilization of intermediate species by the reduction catalyst lowers the energy needed for the reaction to proceed. Overall, the reduction catalyst improves the HER process' efficiency by lowering the energy input needed to produce hydrogen, which is essential for the efficiency of using hydrogen as a fuel on a commercial scale [30].

6. CONCLUSION

Electrochemical water electrolysis is an emerging area of research that facilitates the generation of pure hydrogen and oxygen from water. It is efficient process for converting hydrogen gas into hydrogen energy for storage and utilization. Both the HER and OER catalytic processes are essential for enhancing the efficiency of water electrocatalysis, and their kinetics should be improved to optimize performance. Currently, precious metals are regarded as most effective electrocatalysts. However, the primary challenge is their scarcity on earth and high cost, which limits the widespread application of this technology. Significant research progress has been made to reduce the reliance on precious metals by employing various techniques, such as modifying material compositions and structures, and substituting precious metals with non-precious metal-based catalysts. This review aims to focus on the performance of Al, Ni, Co, and Fe in hydrogen production, highlighting their catalytic activity, efficiency, and potential as non-precious metal-based alternatives for water electrolysis.

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