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Overview of Hydrogen Production by Electrochemical Method; Advantages and Disadvantages

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Abstract – Electrochemical methods are an important technology for environmentally friendly and sustainable hydrogen production. These methods are carried out using electrocatalysts and electrodes. In the hydrogen production process, hydrogen gas is obtained thanks to the electrochemical reactions that take place between the anode and cathode electrodes. On the anode side, hydrogen gas undergoes oxidation and dissociates into hydrogen ions. This reaction occurs when hydrogen molecules lose electrons. Electrocatalysts accelerate the oxidation reaction, enabling the active breakdown of hydrogen. On the cathode side, hydrogen ions and electrons combine to form hydrogen gas. Electrocatalysts increase efficiency by catalyzing the formation of hydrogen gas. Electrochemical hydrogen production is of great importance in reducing dependence on fossil fuels, reducing greenhouse gas emissions and promoting clean energy sources. These methods can use electricity from sources such as solar or wind energy, integrating with renewable energy sources. Electrochemical hydrogen production has advantages such as high efficiency, low emissions, low cost and wide applicability. However, difficulties may also be encountered, such as the activity and durability of electrocatalysts. Research and development focuses on discovering more efficient and economical electrocatalysts and improving the hydrogen production process. In conclusion, electrochemical methods are a promising technology for clean and sustainable hydrogen production and play an important role in the field of energy conversion.

Keywords – Electrochemical, Hydrogen, Electrode, Electrocatalyst, Wastewater

I. Introduction

Hydrogen production from wastewater is one of the wastewater treatment processes to produce hydrogen, a renewable energy source. This process involves the conversion of organic materials in wastewater into hydrogen gas by fermentation or electrochemical methods. Hydrogen production from wastewater can be an environmentally advantageous process because it reduces the amount of waste by recycling organic waste and produces hydrogen gas, a clean energy source. However, there are some challenges in its commercial scale implementation and cost-effectiveness, and continuous research and development is ongoing [1-3].

Biological Hydrogen Production: In this method, organic substances in wastewater are converted into hydrogen gas through bacterial fermentation. This process takes place in anaerobic (without oxygen) conditions. Bacteria metabolize organic matter, producing hydrogen gas and methane as byproducts. Biological hydrogen production is an attractive option due to its low energy consumption and environmental friendliness [4].

Electrochemical Hydrogen Production: In this method, hydrogen gas is produced from wastewater by electrolysis. Electrolysis is the process of splitting water into hydrogen and oxygen gases by applying an electric current. Wastewater is fed into the electrolysis cells and hydrogen gas is generated using electric current. This method provides clean hydrogen production but may be higher in energy consumption and cost [5].

Photofermentation: Photofermentation is a method in which organic substances in wastewater are converted into hydrogen gas using light energy. In particular, organisms such as microalgae and photosynthetic bacteria are used. These organisms carry out the conversion of organic materials into hydrogen gas during photosynthesis. This method is considered as a promising alternative for renewable hydrogen production in wastewater treatment plants [6].

II. Electrochemical Hydrogen Production

Electrochemical hydrogen production is the production of hydrogen gas by splitting water into hydrogen and oxygen gases using a chemical process called electrolysis. Electrolysis is the process of triggering a chemical reaction by applying an electric current. The electrochemical hydrogen production process includes the basic components of the electrolysis cell, water supply and electricity source[7-9]. Electrolysis Cell: The basic component used for electrochemical hydrogen production is the electrolysis cell. This cell is divided into two regions, usually by a membrane or partition between the electrodes. The cell contains anode (oxidation) and cathode (reduction) electrodes that provide the electric current to split water into hydrogen and oxygen gases. Water Source: It is recommended to use pure or purified water for electrochemical hydrogen production. Good quality water provides a more efficient and stable electrolysis process. Electrical Source: An electrical source is required for electrochemical hydrogen production. This is usually an electrical outlet or a power source. Electric current is applied to the electrodes in the electrolysis cell, triggering the formation of hydrogen and oxygen gases. Various wastewater sources can be used for hydrogen production using electrochemical methods. Examples of these are wastewater treatment plant wastewater, industrial wastewater, wastewater from biogas production, and liquid organic wastes. While using electrochemical methods for hydrogen production from these wastewater sources, factors such as wastewater composition, concentration and cleanliness should be considered. It is important to determine the appropriate electrolysis conditions and to optimize the system [1-5].

Hydrogen production from wastewater using electrochemical methods has some advantages and disadvantages. Advantages and disadvantages of hydrogen production by electrochemical methods are given in Table 1. These advantages and disadvantages may affect the feasibility of the electrochemical hydrogen generation process. However, the efficiency of this method is increased, and its costs are reduced by continuously conducting research and development studies.

Table 1. Advantages and disadvantages of hydrogen production from wastewater [1]

Advantages		**Disadvantages**	
Clean Energy Production	Electrochemical hydrogen production enables the production of hydrogen gas, which is a clean energy source. Hydrogen is an environmentally friendly energy source by creating only water vapor during combustion.	Energy Intensity	Electrochemical hydrogen production is an energy-intensive process. Sufficient power supply is needed to produce hydrogen gas using electrical energy. Therefore, energy costs can be high.
Use of Renewable Resources	Wastewater used for electrochemical hydrogen production contains organic materials. These organic materials are a renewable resource and enable the recycling of waste products.	Cost	The electrolysis equipment and systems required for electrochemical hydrogen production can be costly to install and operate. This can make it difficult to implement on a commercial scale.
Combination of Wastewater Treatment and Hydrogen Production	Electrochemical hydrogen production can be used in wastewater treatment plants. In this way, further purification of wastewater can be achieved by converting organic materials into hydrogen gas during the wastewater treatment process.	Efficiency	Efficiency is an important factor in the electrochemical hydrogen production process. The efficiency of electrocatalysts and the electrolysis conditions need to be optimized. Hydrogen production may decrease if high efficiency cannot be achieved.
Waste Reduction and Creating Economic Value	Electrochemical hydrogen production produces hydrogen gas from wastewater, reducing the amount of waste and creating economic value at the same time. Energy production is provided by the evaluation of organic materials in wastewater.	Wastewater Quality and Treatment	The quality and composition of wastewater used for electrochemical hydrogen production is important. Wastewater may need to be pretreated or pretreated. In addition, it may be difficult to obtain adequate amounts and continuity of wastewater for hydrogen production from wastewater sources.

A. *Electrochemical Hydrogen Production Process Steps*

- Preparation of Electrolysis Cell: The electrolysis cell is prepared to be used to separate water into hydrogen and oxygen gases. The electrodes and compartment inside the cell are arranged.
- Electric Current Applied to the Electrodes: A suitable electric current is applied to the anode and cathode electrodes in the electrolysis cell. The anode catalyzes the oxidation reaction, and the cathode catalyzes the reduction reaction.
- Decomposition of Water Molecules: The electric current causes the water molecules in the electrolysis cell to decompose into hydrogen and oxygen gases. While oxygen gas (O_2) is produced in the anode region, hydrogen gas (H_2) is formed in the cathode region.
- Collection of Gases: The hydrogen and oxygen gases formed are collected separately. The hydrogen gas can then be stored or used in other applications.

Electrochemical hydrogen production provides a clean energy source, hydrogen gas. However, the process can be energy intensive and costly to implement on a large scale. For this reason, research and development work is constantly carried out, with a particular focus on the development of more efficient and economical electrocatalysts [10-12].

When using the electrochemical method for hydrogen production from wastewater, it is important to pay attention to the following critical points.

1. Electrocatalyst Selection: Choosing the right electrocatalyst for electrochemical hydrogen production is of great importance. The electrocatalyst accelerates the chemical reactions on the electrode surface and increases efficiency. Choosing an efficient and selective electrocatalyst helps increase hydrogen production efficiency.
2. Electrode Design: The design of the electrodes used for electrochemical hydrogen production is critical. Factors such as electrode material, surface area, structural stability and conductivity affect electrochemical performance. Optimized electrode design can improve hydrogen production efficiency and cell performance.
3. Optimization of Electrolysis Conditions: It is important to set the electrolysis conditions correctly for electrochemical hydrogen production. Factors such as electrolysis current density, temperature, pH value affect hydrogen production efficiency. Optimum electrolysis conditions need to be determined and constantly monitored.
4. Wastewater Pretreatment and Treatment: The quality and composition of wastewater used for hydrogen production from wastewater is important. Using pre-treated or pre-treated wastewater increases the efficiency of electrochemical hydrogen production. It is critical that the necessary pretreatment and refining steps are performed correctly.
5. Power Supply and Energy Efficiency: Electrochemical hydrogen production takes place using electrical energy. Choosing the right power source and ensuring energy efficiency are important. Low energy consumption and high energy efficiency make the hydrogen production process economically and environmentally sustainable.
6. Safety and Sustainability: The safety of the electrochemical hydrogen production process is of paramount importance. Appropriate precautions must be taken, formation of hazardous by-products must be prevented, and safety protocols must be followed. In addition, waste management and recycling must also be considered for the process to be sustainable [9-13].

Correct handling of these critical points increases the efficiency of the electrochemical hydrogen generation process and ensures its safe implementation. Research and development focus on improving these critical points and optimizing the process.

B. *Electrocatalysts and Electrodes*

Various electrocatalysts are used for electrochemical hydrogen production. Some of the commonly used electrocatalysts for electrochemical hydrogen production are given in Table 2. The hydrogen production performance of these electrocatalysts may vary depending on factors such as the surface properties of the electrocatalyst, the amount of catalytic active sites, and the reaction mechanism. Research and development efforts continue towards the discovery of more efficient and economical electrocatalysts.

Table 2. Electrocatalysts used in the production of hydrogen by electrochemical method [7-12]]

Electrocatalysts	Description
Platin (Pt)	Platinum is the most widely used electrocatalyst for electrochemical hydrogen production. Pt electrocatalysts exhibit high hydrogen generation activity and selectivity. However, Pt has disadvantages such as high cost, limited natural resources and tendency to lose its catalytic activity.
Nickel (Ni)	Nickel is an inexpensive and abundantly available electrocatalyst for electrochemical hydrogen production. Nickel electrocatalysts have sufficient activity for hydrogen production. However, due to nickel's high oxidation tendency, its catalytic stability may be limited in some cases.
Nickel Cobalt (Ni-Co) Alloys:	Ni-Co alloys, which are a combination of nickel and cobalt, can show high activity and catalytic stability for hydrogen production. These alloys can catalyze both the electrogenic oxidation of hydrogen and the electrocatalytic redox reactions of hydrogen.
Nickel Molybdenum (Ni-Mo) Alloys	Ni-Mo alloys, which are a combination of nickel and molybdenum, are effective electrocatalysts for hydrogen production. These alloys can increase the efficiency of hydrogen production by catalyzing the electrogenic oxidation of hydrogen.
Inorganic Metal Phosphides	Some inorganic metal phosphides are potential electrocatalysts for electrochemical hydrogen production. Phosphide-based electrocatalysts such as nickel phosphide (NiP), cobalt phosphide (CoP) and iron phosphide (FeP) can be effective in hydrogen production.
Carbon-Based Materials	Carbon-based materials such as graphite, carbon nanotubes, graphene can also be used as electrocatalysts for electrochemical hydrogen production. These materials can offer advantages such as low cost, high surface area, catalytic activity and catalytic stability.

Electrodes used for electrochemical hydrogen production are materials used to perform electrochemical redox reactions of hydrogen. Electrodes along with electrocatalysts are important to increase hydrogen production efficiency and speed up reactions. Commonly used electrode types for electrochemical hydrogen production are given in Table 3. Hydrogen production performance of electrodes depends on factors such as electrode material, surface properties, surface area, structural stability and conductivity. Electrodes are used as anode and cathode in electrochemical cells and are where electrochemical reactions take place. Research and development studies focus on the discovery of more efficient and economical electrode materials and increasing the electrocatalytic activity.

Table 3. Electrodes used in the production of hydrogen by electrochemical method [7-12]

Electrodes	Description
Platinum Electrodes	Platinum electrodes are the most common electrodes used to catalyze the electrochemical oxidation and redox reactions of hydrogen. Platinum electrodes have high electrocatalytic activity and catalytic stability. Especially platinum-coated carbon electrodes are often preferred.
Carbon Electrodes	Carbon electrodes are another type of electrode commonly used for electrochemical hydrogen production. Carbon electrodes derived from graphite have advantages such as high surface area, catalytic activity, and low cost. Different carbon-based materials such as carbon nanotubes, graphene, and micro- or macro-porous carbon structures can be used as electrodes.
Metal Electrodes	Some metal electrodes can also be used for hydrogen production. Metals such as nickel, cobalt and copper are electrode materials used to catalyze the electrochemical oxidation and redox reactions of hydrogen. These metal electrodes can exhibit electrocatalytic activity and catalytic stability.
Metal Phosphide Electrodes	Metal phosphides are potential electrode materials for hydrogen production. Metal phosphides such as nickel phosphide (NiP), cobalt phosphide (CoP), and iron phosphide (FeP) can have electrocatalytic activity and catalytic stability.

C. *The Anode Chamber in The Production of Hydrogen by The Electrochemical Method*

The reactions that take place on the anode side include the electrochemical oxidation of hydrogen. These reactions can be catalyzed using different electrocatalysts and electrode materials. The two main stages of the reactions that take place on the anode side to produce electrochemical hydrogen are described below [1-3,5-9,12,13].

- Oxidation of Hydrogen

Hydrogen gas (H_2) undergoes oxidation at the anode and decomposes into hydrogen ions (H^+). This reaction occurs when hydrogen molecules lose electrons and is usually represented as:

$$H_2 \rightarrow 2H + 2e^-$$

This reaction refers to hydrogen losing electrons at the anode and converting to hydrogen ions. The electrocatalyst accelerates this oxidation reaction, enabling the active breakdown of hydrogen.

- Water Oxidation

Hydrogen ions formed during the oxidation of hydrogen react with water molecules to form oxygen gas (O_2) and hydroxyl ions (OH^-). This reaction is represented as:

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$$
$$4H^+ + 4e^- \rightarrow 2H_20$$

This reaction refers to hydrogen ions reacting with water molecules to form oxygen gas, hydrogen ions and electrons. The electrocatalyst facilitates the release of oxygen gas by catalyzing the water oxidation reaction.

As a result of these reactions, hydrogen gas (H_2) is produced at the anode and electrons flow from the anode. This electron flow creates the electrical current and maintains the hydrogen production process. The reactions taking place on this anode side can have an impact on efficiency, catalytic activity and catalytic stability depending on the choice of electrocatalyst and electrode materials.

D. *Cathode Chamber in Hydrogen Production by Electrochemical Method*

The reactions that take place on the cathode side include electrochemical redox reactions of hydrogen. These reactions can be catalyzed using different electrocatalysts and electrode materials. The two main stages of reactions that take place on the cathode side of electrochemical hydrogen production are given below [1-3,5-9,12,13].

- Redox Reaction of Hydrogen:

Hydrogen ions (H^+) and electrons (e^-) react at the cathode to form hydrogen gas (H_2). This reaction is represented as:

$$2H^+ + 2e^- \rightarrow H_2$$

This reaction refers to the conversion of hydrogen ions into hydrogen gas by reacting with electrons. The electrocatalyst accelerates the formation of hydrogen gas by catalyzing the redox reaction of hydrogen.

- Recombination of Electrons:

Electrons are released at the cathode during the redox reaction of hydrogen. These free electrons often recombine in an electronic flow path to inhibit the formation of oxygen gas (O_2) or hydrogen peroxide (H_2O_2). The recombination reaction allows electrons to recombine with hydrogen ions and form hydrogen gas.

The reactions taking place on the cathode side can affect the efficiency, catalytic activity and catalytic stability depending on the choice of electrocatalyst and electrode materials. Electrocatalysts facilitate the redox reaction of hydrogen and provide efficient formation of hydrogen gas.

The reactions taking place on this cathode side are optimized depending on the properties of the electrocatalyst and electrode materials. Research and development focus on discovering more effective and sustainable cathode materials and increasing electrocatalytic activity.

III. RESULTS

A few potential areas for innovations and improvements in electrochemical hydrogen production include:

Development of Electrocatalysts: The discovery of more active, efficient and economical electrocatalysts is an important step in the development of electrochemical hydrogen production. Research continues for the synthesis of new materials, improving their catalytic activities and increasing their durability.

Electrode Design and Materials: The structure, materials, and geometry of the electrodes can affect hydrogen generation efficiency and electrocatalyst performance. New electrode designs can be developed using properties such as nanostructures that increase surface area, porous structures, and layers with catalytic properties.

Electrochemical Cell Performance: Various factors can be considered to improve the performance of electrochemical cells. For example, cell performance can be increased by strategies such as optimizing the interactions at the electrode-ion interface, increasing the ion conductivity, and improving the electrolyte composition.

Renewable Energy Sources Integration: Electrochemical hydrogen production can be made more environmentally friendly with the use of renewable energy sources. The integration of clean energy sources such as solar or wind energy with electrochemical hydrogen production can provide a sustainable and carbon-reducing hydrogen production.

Catalyst Stability and Durability: The stability and durability of electrocatalysts are important for long-term and efficient hydrogen production. Structural stability and protection measures can be developed to reduce aging and deactivation of catalysts.

Studies can be developed by taking the above points into consideration. Hydrogen energy is one of the promising alternative energy types for the future.

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