

Review Article

Advancements in materials for hydrogen production: A review of cutting-edge technologies

Ahmed Alamiery

Department of Chemical and Process Engineering, Faculty of Engineering and Built Environment, University Kebangsaan Malaysia (UKM), Bangi P.O. Box 43000, Selangor, Malaysia



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ABSTRACT

Hydrogen, a clean and versatile energy carrier, has gained significant attention as a potential solution for addressing the challenges of climate change and energy sustainability. Efficient hydrogen production relies heavily on the development of advanced materials that enable cost-effective and sustainable methods. This review article presents a comprehensive overview of cutting-edge materials used for hydrogen production, covering both traditional and emerging technologies. This article begins by briefly introducing the importance of hydrogen as a clean energy carrier and various methods used for hydrogen production. This emphasizes the critical role of these materials in enabling efficient hydrogen generation. Traditional methods, such as steam methane reforming, coal gasification, biomass gasification, and water electrolysis, are discussed, highlighting the materials used and their advantages and limitations. This review then focuses on emerging technologies that have shown promise for achieving efficient hydrogen production. Photocatalytic water splitting is explored with an emphasis on recent advancements in semiconductor-based photocatalysts and nanostructured materials for enhanced photocatalysis. Solid oxide electrolysis cells (SOEC) are examined, discussing high-temperature electrolysis materials and advancements in electrolytes and electrode materials. Biological hydrogen production and chemical looping are also discussed, highlighting the use of microorganisms, bioengineered systems, metal oxides as oxygen carriers, and catalysts for improved hydrogen generation. Advanced characterization techniques, including X-ray diffraction, spectroscopy, scanning electron microscopy, transmission electron microscopy, X-ray photoelectron spectroscopy, Auger electron spectroscopy, thermogravimetric analysis, and differential scanning calorimetry, have been used to gain insight into the properties and performances of materials. This review concludes by addressing the challenges and prospects in the field of hydrogen production materials. This highlights the importance of the durability, stability, cost-effectiveness, scalability, and integration of materials into large-scale hydrogen production systems. This article also discusses the emerging trends and potential breakthroughs that could shape the future of hydrogen production.

1. Introduction

The global pursuit of clean and sustainable energy sources has led to increased interest in hydrogen as a versatile energy carrier. Hydrogen possesses several desirable characteristics, including high energy density, zero greenhouse gas emissions when utilized, and the potential for various applications, such as transportation, power generation, and industrial processes. As the world shifts towards decarbonization and reduced dependence on fossil fuels, hydrogen is gaining recognition as a key player in clean energy transition [1–4]. Hydrogen has immense potential as a clean energy carrier, because it can be produced from diverse sources and used in a wide range of applications. When utilized, hydrogen produces only water vapor as a byproduct, making it a highly attractive alternative to traditional fossil fuels. The utilization of hydrogen

can significantly contribute to the reduction of greenhouse gas emissions and mitigate the impact of climate change. Moreover, hydrogen can be efficiently stored and transported, providing flexibility in energy distribution and enabling energy access in remote areas [5–9]. Hydrogen can be produced using various methods, each with its own set of advantages and limitations. The most common methods include steam methane reforming (SMR), coal gasification, biomass gasification, and water electrolysis [10]. SMR involves the reaction of natural gas with steam to produce hydrogen and carbon dioxide. Coal and biomass gasification convert solid carbonaceous materials into a gas mixture containing hydrogen. Water electrolysis uses electricity to split water into hydrogen and oxygen [11,12]. These methods have different energy requirements, costs, and environmental impacts, and the selection of a production method depends on factors such as feedstock availability, infrastructure,

E-mail addresses: dr.ahmed1975@ukm.edu.my, p109960@siswa.ukm.edu.my

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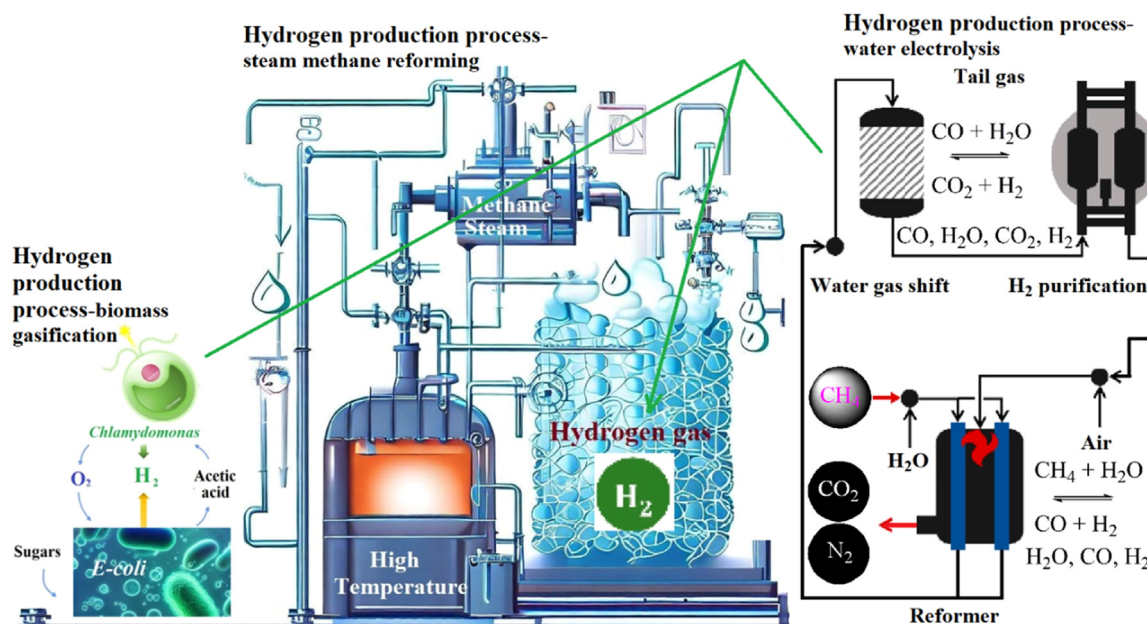


Fig. 1. Schematic of the hydrogen production process.

and local regulations. Materials play a crucial role in hydrogen production processes by enabling efficient and sustainable production [13,14]. The selection and design of appropriate materials are vital for improving the reaction kinetics, enhancing catalyst performance, ensuring durability, and minimizing energy consumption. Catalytic materials such as nickel-based alloys are essential for efficient hydrogen generation in steam-methane reforming [15,16]. Gasification requires materials that can withstand high temperature and corrosive environments. Electrolysis techniques rely on materials with excellent electrocatalytic properties for water splitting and on robust ion-conductive membranes for efficient proton and oxygen ion transport [17,18]. The schematic in Fig. 1 provides an overview of the hydrogen production process. It visually depicts the different methods and materials involved in hydrogen production, including steam methane reforming, water electrolysis, biomass gasification, and photovoltaic electrolysis. This figure illustrates the interconnectedness of the various stages of hydrogen production and helps readers understand the overall process.

The development of advanced materials is essential to overcome the challenges associated with hydrogen production methods. Researchers are actively exploring innovative materials, including novel catalysts, membrane materials, and nanostructured materials, to improve the reaction efficiency, reduce energy requirements, and enhance the durability of hydrogen production systems. The significance of hydrogen as a clean energy carrier is gaining worldwide recognition [19,20]. This offers a promising solution for addressing climate change and achieving sustainable energy production. Various hydrogen production methods, such as SMR, coal and biomass gasification, and water electrolysis, provide options for diverse feedstocks and energy sources. Materials are integral to the success of hydrogen production processes, influencing reaction kinetics, catalyst performance, and system durability [21,22]. Continued advancements in materials science and engineering are crucial for realizing efficient and sustainable large-scale hydrogen production methods. The aim of this review is to provide a comprehensive analysis of recent advancements in hydrogen production materials and their role in advancing the field of clean energy. The objectives of this study are summarized as follows:

1. To explore the importance of hydrogen as a sustainable and clean energy carrier in the context of global energy transition and decarbonization efforts.

2. To review the traditional methods and materials used for hydrogen production, including steam methane reforming, water electrolysis, biomass gasification, and photovoltaic electrolysis.
3. To examine cutting-edge advancements in materials for hydrogen production, including catalysts, membranes, and nanostructured materials, and assess their potential for improving efficiency, selectivity, and sustainability.
4. To analyze the impact of material characteristics such as composition, structure, and morphology on the performance of hydrogen production technologies.
5. To discuss the challenges associated with integrating advanced materials into hydrogen production systems, including scalability, durability, cost-effectiveness, and long-term stability.
6. To explore emerging trends and future prospects in material research for hydrogen production, such as the utilization of renewable resources, novel synthesis techniques, and the development of multifunctional materials.
7. To provide insights into the role of material characterization techniques in understanding the structure-property relationships of hydrogen production materials and guiding the design of advanced materials.
8. To emphasize the importance of interdisciplinary collaboration and knowledge exchange among researchers, engineers, and policymakers in advancing the field of hydrogen production materials.
9. Identify key research directions and priorities for further advancements in materials science and engineering to enable efficient, sustainable, and economically viable hydrogen production technologies.

2. Traditional materials for hydrogen production

2.1. Steam methane reforming (SMR)

Steam methane reforming (SMR) is the most widely used industrial hydrogen production method. In SMR, methane (natural gas) reacts with steam over a catalyst to produce hydrogen and carbon dioxide. Catalysts play a crucial role in facilitating the reactions and improving the overall efficiency of the process [23]. Traditional catalyst materials for SMR include nickel-based alloys such as nickel-molybdenum or nickel-ruthenium supported on high-surface-area materials such as alumina

Table 1
Comparison of traditional hydrogen production methods.

Hydrogen production method	Advantages	Disadvantages
Steam methane reforming	High hydrogen yield, mature technology, cost-effective	Carbon emissions, reliance on fossil fuels
Coal gasification	Utilization of abundant coal resources, high hydrogen yield	Carbon emissions, environmental concerns, gasification process complexity
Biomass gasification	Utilization of renewable biomass feedstock, carbon-neutral potential	Lower hydrogen yield, feedstock availability, gasification process optimization
Water electrolysis	Direct production of pure hydrogen, no carbon emissions	High energy input, cost-intensive, dependence on electricity generation methods

or silica [24,25]. These catalysts promote reforming reactions and help achieve high rates of methane conversion into hydrogen. Nickel-based catalysts are favored because of their excellent activity, selectivity, and resistance to deactivation caused by carbon formation [26]. However, challenges persist in SMR owing to catalyst deactivation over time, primarily resulting from carbon deposition on the catalyst surface [27,28]. The formation of carbonaceous species reduces the catalyst activity and requires periodic regeneration or replacement. Researchers are actively exploring advanced catalyst formulations and novel catalyst supports to improve the stability and durability of the SMR catalysts [29,30]. Table 1 highlights the advantages and disadvantages of traditional hydrogen production methods. Steam methane reforming (SMR) is a well-established cost-effective method with a high hydrogen yield. However, they rely on fossil fuels for carbon emissions. Coal gasification offers the advantage of utilizing abundant coal resources but also comes with environmental concerns and process complexity. Biomass gasification is a renewable option with carbon-neutral potential; however, it has challenges related to lower hydrogen yield and feedstock availability. Water electrolysis offers a direct route to pure hydrogen without carbon emissions; however, it requires significant energy input and can be expensive.

2.2. Coal gasification

Coal gasification involves converting coal into a gas mixture containing hydrogen, carbon monoxide, carbon dioxide, and other gasses. This process offers an alternative pathway for hydrogen production and utilizes various types of coal as feedstock [31,32]. Materials used in coal gasification must withstand extreme conditions, including high temperatures and pressures, as well as corrosive environments. Refractory materials such as ceramics and metal alloys are commonly employed in gasifiers to handle harsh operating conditions. These materials exhibit excellent thermal stability, chemical resistance, and mechanical strength, ensuring the integrity of gasifier components and preventing premature failure [33,34].

2.3. Biomass gasification

Biomass gasification is a renewable approach to hydrogen production that utilizes organic materials such as agricultural residues, wood chips, and energy crops. Similar to coal gasification, biomass gasification involves the conversion of biomass into a gas mixture containing hydrogen, carbon monoxide, carbon dioxide, and other byproducts [35]. The selection of materials for biomass gasification is influenced by the composition of the biomass feedstock and gasification process conditions. Biomass gasification systems often require robust refractory materials similar to those used in coal gasification to withstand high temperatures and corrosive environments. Additionally, the choice of materials should consider the potential presence of alkali and tar contaminants, which can cause fouling and corrosion [36,37].

2.4. Water electrolysis

Water electrolysis is an electrochemical process in which water molecules are split into hydrogen and oxygen gasses using an electric current. Two primary electrolysis methods are widely employed:

alkaline electrolysis (AE) and proton exchange membrane electrolysis (PEM). In AE, materials such as nickel or nickel-based alloys are typically used as electrode materials, while potassium hydroxide (KOH) serves as the electrolyte [38,39]. Electrodes should have good electrical conductivity, corrosion resistance, and stability during electrolysis. Ni-based electrodes are favored because of their high catalytic activity for hydrogen evolution and resistance to corrosion. PEM electrolysis relies on proton-conducting membranes typically based on perfluoro-sulfonic acid polymers such as Nafion [40–43]. These membranes allow selective proton transport, while blocking the passage of other gasses. The choice of the membrane material is critical for ensuring high proton conductivity, mechanical stability, chemical resistance, and long-term durability under operating conditions. Continued research efforts have focused on developing advanced materials for electrolysis, including new electrode catalysts, non-precious metal catalysts, and innovative proton-exchange membrane materials, with the aim of enhancing the energy efficiency, reducing costs, and improving the overall system performance. In summary, traditional materials for hydrogen production such as steam methane reforming, coal gasification, biomass gasification, and water electrolysis play pivotal roles in the efficiency and performance of these processes [44–46]. The selection and development of appropriate materials are crucial for achieving high conversion rates, durability, and cost-effectiveness of hydrogen production systems [47,48]. Ongoing research on catalyst design, refractory materials, and electrolysis components will contribute to the advancement of traditional hydrogen production methods and facilitate the transition to a sustainable hydrogen economy [49,50]. Table 2 lists catalysts used for hydrogen production via water electrolysis. Platinum (Pt) is widely recognized for its high electrocatalytic activity, which makes it suitable for both proton-exchange membrane (PEM) electrolysis and alkaline electrolysis. Iridium (Ir) offers excellent stability at high current densities, making it valuable under demanding electrolytic conditions. Nickel (Ni) is a low-cost and abundant catalyst with applications in alkaline and solid oxide electrolysis. Ruthenium (Ru) exhibits enhanced catalytic activity and is utilized in PEM and alkaline electrolysis. Cobalt (Co) shows promise as a promising cost-effective alternative to noble metals and is used in both PEM and alkaline electrolysis systems. These catalysts play vital roles in facilitating the efficient and sustainable production of hydrogen through water electrolysis.

3. Emerging materials for hydrogen production

3.1. Photocatalytic water splitting

Table 3 showcases nanostructured materials utilized for enhanced photocatalysis in hydrogen production. Titanium dioxide (TiO₂) is known for its high photocatalytic efficiency and finds applications in photocatalytic water splitting and solar fuel production. Zinc oxide (ZnO) offers a wide bandgap and high electron mobility, making it suitable for photocatalytic water splitting and pollutant degradation. Tungsten trioxide (WO₃) exhibits visible light absorption, enabling its use in photocatalytic water splitting and environmental remediation [49,50]. Bismuth vanadate (BiVO₄) demonstrates visible light absorption and stability, making it valuable for photocatalytic water splitting and solar fuel production. Graphene-based materials possess a high surface area and

Table 2
Catalysts for hydrogen production via water electrolysis.

Catalyst	Advantages	Applications
Platinum (Pt)	High electrocatalytic activity	Proton exchange membrane (PEM) electrolysis
Iridium (Ir)	Excellent stability at high current densities	PEM electrolysis, alkaline electrolysis
Nickel (Ni)	Low cost, abundance	Alkaline electrolysis, solid oxide electrolysis
Ruthenium (Ru)	Enhanced catalytic activity	PEM electrolysis, alkaline electrolysis
Cobalt (Co)	Promising alternative to noble metals	PEM electrolysis, alkaline electrolysis

Table 3
Nanostructured materials for enhanced photocatalysis.

Material	Advantages	Applications
Titanium dioxide (TiO ₂)	High photocatalytic efficiency	Photocatalytic water splitting, solar fuel production
Zinc oxide (ZnO)	Wide bandgap, high electron mobility	Photocatalytic water splitting, pollutant degradation
Tungsten trioxide (WO ₃)	Visible light absorption	Photocatalytic water splitting, environmental remediation
Bismuth vanadate (BiVO ₄)	Visible light absorption, stability	Photocatalytic water splitting, solar fuel production
Graphene-based materials	High surface area, electron transport	Photocatalytic water splitting, energy conversion

Table 4
Advances in semiconductor-based photocatalysts.

Semiconductor material	Advantages	Applications
Titanium dioxide (TiO ₂)	Abundant, nontoxic, photochemical stability	Photocatalytic water splitting, hydrogen production
Zinc oxide (ZnO)	Low cost, visible light activity	Photocatalytic water splitting, solar fuel production
Tungsten trioxide (WO ₃)	Visible light activity, charge separation efficiency	Photocatalytic water splitting, hydrogen generation
Cadmium sulfide (CdS)	High quantum yield, tunable bandgap	Photocatalytic water splitting, hydrogen production
Bismuth vanadate (BiVO ₄)	Visible light absorption, good charge carrier mobility	Photocatalytic water splitting, solar fuel production

efficient electron transport, contributing to their use in photocatalytic water splitting and energy conversion.

3.1.1. Advances in semiconductor-based photocatalysts

Photocatalytic water splitting is a promising approach for hydrogen production that utilizes sunlight to drive water splitting reactions. Semiconductor-based photocatalysts play a crucial role in this process by absorbing light and initiating the redox reactions. Significant advancements have been achieved in the development of semiconductor-based photocatalysts [51,52]. Materials such as titanium dioxide (TiO₂), zinc oxide (ZnO), and various metal oxides have shown promise because of their suitable bandgap energies, high stabilities, and abundant availability. Researchers are actively exploring strategies for enhancing the photocatalytic performance of these materials through surface modification, doping, and nanostructuring. These approaches aim to improve the light absorption, charge separation, and catalytic efficiency, leading to increased hydrogen production rates [53,54]. Table 4 highlights advances in semiconductor-based photocatalysts for water splitting and hydrogen production. Titanium dioxide (TiO₂) has been widely studied owing to its abundance, nontoxicity, and photochemical stability. Zinc oxide (ZnO) is a low-cost material with visible light activity. Tungsten trioxide (WO₃) provides visible light activity and efficient charge separation. Cadmium sulfide (CdS) exhibits high quantum yield and tunable bandgap. Bismuth vanadate (BiVO₄) exhibits excellent visible light absorption and charge carrier mobility. These materials exhibit potential for photocatalytic water splitting and hydrogen generation applications.

3.1.2. Nanostructured materials for enhanced photocatalysis

Nanostructured materials have emerged as a key research area for enhancing the efficiency of photocatalytic water splitting [55]. By manipulating the size, shape, and composition of nanoparticles or nanostructured architectures, researchers can tailor the optical and electronic properties of materials. Various nanostructured materials, including metal nanoparticles, metal oxides, quantum dots, and nanocomposites, have demonstrated improved photocatalytic performance [56]. These nanostructures provide an increased surface area, reduced charge carrier recombination, and enhanced light absorption, leading to enhanced hydrogen generation. Additionally, the integration of nanostructures with

cocatalysts or cocoon-like protective layers further boosts the stability and catalytic activity of the photocatalysts [57].

3.1.3. Reaction mechanism of photocatalytic water splitting

Photocatalytic water splitting utilizes light energy to split water (H₂O) into its constituent elements: hydrogen (H₂) and oxygen (O₂). This process typically occurs on the surface of a photocatalytic material that absorbs photons and initiates a series of chemical reactions. Understanding the reaction mechanism is crucial to understand the intricacies of this sustainable and environmentally friendly hydrogen production method.

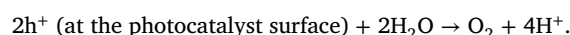
3.1.3.1. Light absorption.

The process begins with the absorption of photons by a photocatalyst material, which is often a semiconductor such as titanium dioxide (TiO₂), cadmium sulfide (CdS), or other suitable materials. The energy of the absorbed photons promotes electrons from the valence band to the conduction band of the semiconductor, creating electron-hole pairs (e⁻-h⁺). This electronic excitation is the fundamental step that initiates the subsequent reactions.

3.1.3.2. Redox reactions.

The separated electrons (e⁻) in the conduction band and holes (h⁺) in the valence band of the photocatalyst participate in redox (reduction-oxidation) reactions at the surface of the photocatalyst. In water splitting, two half-reactions occur simultaneously:

Oxygen evolution reaction (OER): At the anode, holes (h⁺) in the valence band react with water molecules to generate oxygen gas (O₂) and protons (H⁺):



Hydrogen evolution reaction (HER): At the cathodic site, electrons (e⁻) in the conduction band reduce protons (H⁺) to form hydrogen gas (H₂):



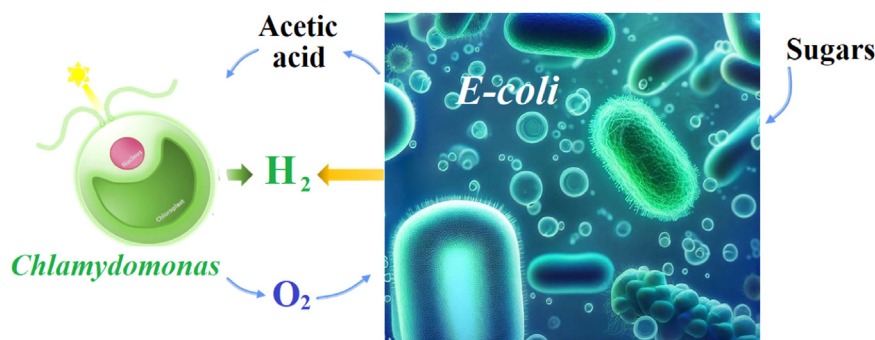


Fig. 2. Microorganisms for biohydrogen generation.

Table 5

High-temperature electrolysis materials for solid oxide electrolysis cells (SOEC).

Electrolyte material	Advantages	Applications
Yttria-stabilized zirconia (YSZ)	High ionic conductivity, chemical stability	Solid oxide electrolysis cells (SOEC) for hydrogen production
Gadolinium-doped ceria (GDC)	Enhanced oxygen ion transport, tolerance to carbon deposition	Solid oxide electrolysis cells (SOEC), syngas production
Scandia-stabilized zirconia (ScSZ)	High conductivity, enhanced durability	Solid oxide electrolysis cells (SOEC), hydrogen production
BaZr _{0.1} Ce _{0.7} Y _{0.2} O ₃ (BZCY)	Proton-conducting electrolyte, lower operating temperature	Solid oxide electrolysis cells (SOEC), hydrogen production
La _{0.9} Sr _{0.1} Ga _{0.8} Mg _{0.2} O ₃ (LSGM)	High ionic conductivity, chemical compatibility	Solid oxide electrolysis cells (SOEC), hydrogen production

These half-reactions are critical for the overall water splitting process and occur simultaneously at the surface of the photocatalyst.

3.1.3.3. Cocatalysts and surface reactions.

In practice, to enhance the efficiency of photocatalytic water splitting, cocatalysts are often introduced onto the photocatalyst's surface. Cocatalysts, which are typically noble metals like platinum (Pt) or cocatalytic semiconductors such as nickel oxide (NiO), facilitate redox reactions by serving as active sites for hydrogen and oxygen evolution. The generated hydrogen and oxygen gasses can then be collected and separated for various applications such as fuel cells and other energy conversion processes.

In summary, photocatalytic water splitting relies on the absorption of light by a photocatalyst material, generating electron-hole pairs that initiate redox reactions at the surface of the photocatalyst. These reactions lead to the production of hydrogen and oxygen gasses, making this process a promising method for sustainable hydrogen production. The efficiency of photocatalytic water splitting can be further enhanced through the introduction of cocatalysts and careful engineering of photocatalyst materials.

3.2. Solid oxide electrolysis cells (SOEC)

3.2.1. High-temperature electrolysis materials

Solid-oxide electrolysis cells (SOECs) enable the direct electrochemical splitting of water into hydrogen and oxygen at high temperatures. The performance and efficiency of SOECs depend on the materials employed for the electrolyte and electrodes. Materials with high ionic conductivities and stabilities at elevated temperatures are crucial for electrolytes. Yttria-stabilized zirconia (YSZ) and doped ceria (CeO₂) are commonly used as electrolyte materials in SOECs [58,59]. These materials offer excellent oxygen-ion conductivity and mechanical strength, ensuring efficient ion transport and durability. Advancements in electrode materials have also played a significant role in improving the SOEC performance. Perovskite-type oxides, such as strontium-doped lanthanum manganite (LSM) and nickelates, are widely employed as cathode materials owing to their good oxygen reduction kinetics. Anode materials such as nickel-based cermet and perovskites have been developed to facilitate the hydrogen evolution reaction [60–62].

3.2.2. Advances in electrolyte and electrode materials

Research has focused on exploring new electrolytes and electrode materials to enhance the performance and efficiency of SOECs. Materials such as scandia-stabilized zirconia (ScSZ), gadolinium-doped ceria (GDC), and proton-conducting oxides have been investigated as alternative electrolytes to improve ionic conductivity and reduce ohmic losses [63,64]. In addition, innovative electrode materials, including mixed ionic-electronic conductors and novel catalysts, have been developed to enhance reaction kinetics and minimize electrode polarization. Strategies such as surface modifications, nanostructuring, and catalyst incorporation aim to improve electrode performance, ion transport, and overall cell efficiency [61,65]. Table 5, presents high-temperature electrolysis materials used in SOECs for hydrogen production. Yttria-stabilized zirconia (YSZ) offers high ionic conductivity and chemical stability. Gadolinium-doped ceria (GDC) enhances the oxygen ion transport and carbon deposition tolerance. Scandia-stabilized zirconia (ScSZ) exhibits high conductivity and durability. BaZr_{0.1}Ce_{0.7}Y_{0.2}O₃ (BZCY) is a proton-conducting electrolyte operating at low temperatures. La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O₃ (LSGM) exhibits high ionic conductivity and chemical compatibility. These materials are crucial for the development of efficient and durable oxide electrolysis cells for hydrogen production.

3.3. Biological hydrogen production

Fig. 2 presents a visual representation of the microorganisms used for biohydrogen generation. This may include images or diagrams illustrating the specific microorganisms involved in hydrogen production and their metabolic pathways. This figure enhances our understanding of biological hydrogen production and highlights the potential of harnessing microbial systems for sustainable hydrogen generation.

3.3.1. Microorganisms for biohydrogen generation

Biological hydrogen production utilizes microorganisms that are capable of producing hydrogen through various metabolic pathways. Certain microorganisms, such as purple bacteria, green algae, and photosynthetic bacteria can generate hydrogen through photosynthesis or fermentation processes [66,67]. Advances in the understanding of microbial physiology and genetic engineering techniques have enabled the development of genetically modified microorganisms with enhanced hydrogen production capabilities. These bioengineered systems can opti-

Table 6
Microorganisms for biohydrogen generation.

Microorganism	Advantages	Applications
Clostridium spp.	High hydrogen yield, broad substrate range	Biohydrogen production from organic waste, biofuel production
Rhodobacter capsulatus	Photosynthetic bacteria, direct hydrogen production	Biohydrogen production from sunlight and organic compounds
Chlamydomonas reinhardtii	Green algae, efficient hydrogen production	Biohydrogen production from sunlight and water
Escherichia coli	Genetic engineering potential, hydrogen production via synthetic pathways	Biohydrogen production using engineered microbial systems
Thermotoga spp.	Thermophilic bacteria, high-temperature hydrogen production	Biohydrogen production from high-temperature environments

Table 7
Metal oxides as oxygen carriers in chemical looping for hydrogen production.

Metal oxide	Advantages	Applications
Iron oxide	Abundance, low cost, strong oxygen-carrying capacity	Chemical looping for hydrogen production, syngas production
Nickel oxide	High reactivity, excellent oxygen transport properties	Chemical looping for hydrogen production, CO ₂ capture
Copper oxide	Efficient oxygen transfer, good redox stability	Chemical looping for hydrogen production, syngas production
Cobalt oxide	Stable oxygen release, suitable for high-temperature applications	Chemical looping for hydrogen production, syngas production
Manganese oxide	Moderate oxygen release, versatile oxygen carrier	Chemical looping for hydrogen production, CO ₂ capture

mize hydrogen production pathways, improve substrate utilization, and increase hydrogen yield [68,69].

3.3.2. Bioengineered systems for enhanced hydrogen production

Bioengineered systems for hydrogen production involve the integration of microorganisms with various support materials such as immobilized cells or enzyme-coated electrodes. These systems provide a controlled environment for microorganisms, optimize mass transfer, and enhance the hydrogen production rates [70]. Furthermore, the coupling of biological hydrogen production with waste treatment processes such as anaerobic digestion or wastewater treatment allows for simultaneous energy recovery and environmental remediation. Integration with renewable feedstocks such as lignocellulosic biomass or organic waste provides sustainable substrates for microbial hydrogen generation [71,72]. Table 6 lists various microorganisms used for biohydrogen generation. Clostridium spp. are known for their high hydrogen yield and ability to utilize a broad range of substrates, making them suitable for biohydrogen production from organic waste and biofuel production. Rhodobacter capsulatus is a photosynthetic bacterium that produces hydrogen directly from sunlight and organic compounds. Chlamydomonas reinhardtii is a green algae that efficiently produces hydrogen from sunlight and water. Escherichia coli has genetic engineering potential, allowing the production of hydrogen via synthetic pathways. Thermotoga spp. are thermophilic bacteria capable of producing hydrogen at high temperatures, which is beneficial for biohydrogen production in high-temperature environments.

3.3.3. Chemical looping for hydrogen production

3.3.3.1. Metal oxides as oxygen carriers.

Chemical looping is a promising technology that uses metal oxides as oxygen carriers to generate hydrogen. In this process, a metal oxide is exposed to a reducing agent such as methane or syngas, resulting in the reduction of the metal oxide and the release of oxygen. The reduced metal oxide is then re-oxidized using air or steam, regenerating the oxygen carrier for subsequent cycles [73,74]. Various metal oxides, including iron oxide (Fe₂O₃), copper oxide (CuO), and manganese oxide (MnO), have been investigated as oxygen carriers for chemical-looping hydrogen production. These materials exhibit high reactivities, good oxygen capacities, and high stabilities over multiple redox cycles [75,76].

3.3.3.2. Catalysts for efficient hydrogen generation.

Efficient hydrogen generation in chemical-looping systems requires catalysts to facilitate the reactions involved in oxygen-carrier regeneration and hydrogen production. Catalysts promote desired reactions,

enhance reaction rates, and reduce energy requirements. Various catalyst materials, such as nickel-based catalysts, precious metals (e.g., platinum and palladium), and mixed metal oxides, have been employed to improve hydrogen generation efficiency in chemical looping processes [77,78]. Catalyst design focuses on optimizing surface area, activity, and selectivity, enabling efficient oxygen carrier regeneration and hydrogen production. In conclusion, emerging materials for hydrogen production offer exciting opportunities for enhancing efficiency, reducing costs, and enabling sustainable hydrogen generation. Advances in semiconductor-based photocatalysts, nanostructured materials, solid oxide electrolysis cells, biological hydrogen production, and chemical looping have contributed to the development of efficient and environment-friendly hydrogen production technologies. Continued research and innovation in these materials holds great potential for driving the widespread adoption of hydrogen as a clean energy source [79–81]. Table 7 lists the metal oxides used as oxygen carriers in chemical looping for hydrogen production. Iron oxide is advantageous because of its abundance, low cost, and high oxygen-carrying capacity. Nickel oxide exhibits high reactivity and excellent oxygen transport properties. CuO offers efficient oxygen transfer and good redox stability. Cobalt oxide provides a stable oxygen release, making it suitable for high-temperature applications. Manganese oxide exhibits moderate oxygen release and versatility as an oxygen carrier. These metal oxides play crucial roles in the chemical looping processes for hydrogen production, syngas production, and CO₂ capture applications.

4. Advances in materials characterization techniques

4.1. X-ray diffraction (XRD) and spectroscopy

X-ray diffraction (XRD) is a technique widely used for analyzing the crystal structure and phase composition of materials. It provides valuable information regarding the arrangement of atoms within a material and helps determine the crystallographic phases present. Recent advancements in XRD include the development of high-resolution detectors, such as charge-coupled devices (CCD) and area detectors, which enable rapid data acquisition and improved sensitivity [82,83]. Additionally, synchrotron-based XRD techniques offer enhanced capabilities such as high credibility and tunable energy, allowing for detailed investigations of the structural properties of materials. X-ray spectroscopy techniques, such as X-ray photoelectron spectroscopy (XPS) and X-ray absorption spectroscopy (XAS), provide valuable insights into the electronic and chemical states of materials. These techniques help understand the surface composition, oxidation states, and chemical bonding characteristics of materials, facilitating the study of catalysts, electrode materials, and functional coatings [84–86].

4.2. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM)

Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are powerful tools for visualizing the microstructure and morphology of materials at different scales. SEM provides high-resolution imaging and allows for elemental analysis using energy-dispersive X-ray spectroscopy (EDS). Recent advancements in SEM technology have led to improved resolution, better detection limits, and integration of in situ capabilities [87–89]. Environmental SEM (ESEM) enables imaging under controlled humidity or gas environments, providing insights into the behavior of materials under realistic conditions. TEM offers even higher resolution and enables the visualization of materials at the atomic scale. Advanced TEM techniques such as high-resolution TEM (HRTEM), electron diffraction, and electron energy-loss spectroscopy (EELS) provide valuable information on crystal defects, interfaces, and chemical mapping. In situ TEM techniques allow the observation of dynamic processes such as phase transformations and nanoscale reactions in real time [90,91].

4.3. X-ray photoelectron spectroscopy (XPS) and Auger electron spectroscopy (AES)

X-ray photoelectron spectroscopy (XPS) and Auger electron spectroscopy (AES) are surface-sensitive techniques used to analyze the elemental composition, chemical bonding, and electronic states of materials. XPS provides information on the elemental composition and chemical states of the surface species by measuring the binding energies of the photoemitted electrons. Recent advancements in XPS include increased energy resolution, multi-technique capabilities (e.g., combining XPS with depth profiling or angle-resolved measurements), and integration of imaging capabilities for spatially resolved analysis [92,93]. AES is a technique complementary to XPS that provides information about the elemental composition and chemical states of surface layers. It involves the detection of Auger electrons emitted during relaxation processes following core-level ionization. Advances in AES include improved energy resolution, depth-profiling capabilities, and the ability to perform elemental mapping [94,95].

4.4. Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC)

Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) are techniques used to investigate the thermal behavior, stability, and phase transitions of materials. Thermogravimetric analysis (TGA) measures the weight change of a material as a function of the temperature. It provides information on processes, such as thermal decomposition, desorption, and oxidation. Recent advancements in TGA include the integration of evolved gas analysis (EGA) techniques such as mass spectrometry (MS) or Fourier transform infrared spectroscopy (FTIR), which enable the identification and quantification of gaseous products released during thermal events [96,97]. DSC measures the heat flow associated with exothermic or endothermic processes as a function of the temperature. It provides information on phase transitions, crystallization, melting, and reaction enthalpies. Recent advancements in DSC technology include improved sensitivity, high-speed scanning capabilities, and the integration of hyphenated techniques for simultaneous measurements, such as coupling DSC with FTIR or gas chromatography-mass spectrometry (GC-MS). In conclusion, advances in material characterization techniques, such as XRD, spectroscopy, SEM, TEM, XPS, AES, TGA, and DSC, have greatly enhanced our ability to understand the structure, composition, and thermal properties of materials used in hydrogen production. These techniques provide valuable insights into the performance and behavior of materials, aiding the design and optimization of hydrogen production systems [33,98].

Table 8
Challenges and potential solutions in large-scale hydrogen production.

Challenge	Potential solutions
Scalability of hydrogen production	Development of efficient and modular production systems
Cost-effectiveness of materials	Advancements in material synthesis and manufacturing
Durability and stability of materials	Research on durable and long-lasting materials
Integration with existing energy infrastructure	Retrofitting and integration of hydrogen production systems
Minimization of environmental impact	Development of sustainable production processes

5. Challenges and future outlook

5.1. Durability and stability of materials

One of the key challenges in the field of hydrogen production materials is ensuring their long-term durability and stability under harsh operating conditions. Many hydrogen production methods involve high temperatures, corrosive environments, and cycling between reducing and oxidizing atmospheres, which can degrade materials over time [32,99–101]. Material degradation can result in reduced performance, decreased efficiency, and increased maintenance costs. Therefore, it is essential to develop materials that can withstand these challenging conditions without compromising their functionality. Research has focused on exploring new materials and coatings with improved corrosion resistance, thermal stability, and mechanical strength. In addition, advanced characterization techniques and accelerated testing methodologies have been employed to evaluate and predict material degradation mechanisms, enabling the design of more robust materials for hydrogen production [102,103].

5.2. Cost-effectiveness and scalability

Another significant challenge in the widespread adoption of hydrogen production materials is achieving cost-effectiveness and scalability. Many materials used in hydrogen production processes, such as catalysts and membranes, rely on scarce or expensive raw materials, which hinders their large-scale deployment. To overcome this challenge, researchers have aimed to develop alternative materials that are abundant, low-cost, and efficient [104]. For example, the exploration of non-precious metal catalysts, earth-abundant materials, and nanomaterials with enhanced catalytic properties could significantly reduce the overall cost of hydrogen production. Furthermore, advancements in manufacturing techniques such as scalable synthesis methods and innovative reactor designs are being pursued to optimize production processes and reduce fabrication costs [105].

5.3. Integration of materials in large-scale hydrogen production

The integration of materials into large-scale hydrogen production systems poses unique challenges. As the demand for hydrogen increases, it has become crucial to develop materials and technologies that can be seamlessly integrated into existing infrastructure and processes. Efficient coupling of materials with hydrogen production methods such as steam methane reforming or electrolysis requires careful consideration of factors such as compatibility, performance, and system integration [106,107]. Materials must be tailored to meet the specific requirements of each hydrogen production method while ensuring compatibility with other components and system constraints. This integration also involves addressing issues related to heat management, safety, and process optimization [108]. Table 8 summarizes the challenges of large-scale hydrogen production and proposes potential solutions. The scalability of hydrogen production can be addressed by developing efficient modular

production systems that can be expanded easily. Cost-effectiveness can be improved through advancements in material synthesis and manufacturing techniques, enabling the use of affordable and abundant materials. The durability and stability of materials can be enhanced through dedicated research efforts focused on the development of durable and long-lasting materials. Integration with existing energy infrastructure requires retrofitting and integrating hydrogen production systems into the current energy landscape. Finally, the environmental impact can be minimized by developing sustainable production processes that utilize renewable resources and minimize emissions.

5.4. Emerging trends and potential breakthroughs

The field of materials for hydrogen production is witnessing several emerging trends and breakthroughs that hold promise for the future. Some of these include [109–112]:

- Advanced catalysts:** The development of novel catalysts with high activity, selectivity, and stability is the focus of ongoing research. Advances in catalyst design, such as single-atom catalysts, alloy catalysts, and hybrid materials, have shown potential for improving the efficiency of hydrogen production.
- Advanced membranes:** Membranes play a crucial role in processes, such as hydrogen purification and separation. Advanced membranes with high selectivity, permeability, and stability can significantly enhance the efficiency and cost-effectiveness of hydrogen production and purification.
- Energy-efficient processes:** Energy efficiency is a critical aspect of sustainable hydrogen production. Research has focused on developing energy-efficient processes such as electrochemical processes, thermochemical cycles, and integrated systems that utilize waste heat or renewable energy sources.
- Materials for energy storage:** Hydrogen has significant potential as an energy-storage medium. Advancements in materials for hydrogen storage, such as metal hydrides, chemical hydrides, and porous materials, are being pursued to enable the efficient and safe storage and release of hydrogen for various applications.
- Sustainable materials:** The development of sustainable and environmentally friendly materials has gained attention. These include materials derived from renewable resources, materials with reduced environmental impact throughout their lifecycle, and materials that facilitate the use of renewable energy sources for hydrogen production.

In conclusion, addressing the challenges related to durability, cost-effectiveness, scalability, and integration of materials is crucial for advancing hydrogen production. Continued R&D efforts, along with emerging trends and potential breakthroughs, will play a vital role in realizing the full potential of these materials for sustainable and efficient hydrogen production.

6. Conclusion

In conclusion, the field of materials for hydrogen production is rapidly evolving, driven by increasing demand for clean and sustainable energy sources. Materials play a critical role in hydrogen production by influencing their efficiency, performance, and cost-effectiveness. This review article provides an overview of cutting-edge developments in materials for hydrogen production, covering traditional materials, emerging materials, material characterization techniques, challenges, and future prospects. The importance of hydrogen as a clean energy carrier has been emphasized, highlighting its potential to mitigate greenhouse gas emissions and address energy sustainability challenges. Various hydrogen production methods, including steam methane reforming, coal gasification, biomass gasification, water electrolysis, photocatalytic water splitting, solid oxide electrolysis, biological hydrogen production, and chemical looping, are discussed along with the materials associated with

each method. This review also explores advances in material characterization techniques, such as X-ray diffraction, spectroscopy, scanning electron microscopy, transmission electron microscopy, X-ray photoelectron spectroscopy, Auger electron spectroscopy, thermogravimetric analysis, and differential scanning calorimetry. These techniques provide valuable insight into the structural, compositional, and thermal properties of materials, aiding in their design, optimization, and performance evaluation. Furthermore, the challenges and prospects of materials for hydrogen production were examined. The durability and stability of materials, cost-effectiveness and scalability, integration into large-scale production systems, emerging trends, and potential breakthroughs have been identified as key areas of focus. Overcoming these challenges and capitalizing on emerging trends is crucial for the widespread adoption of materials for hydrogen production and the realization of a sustainable hydrogen economy. Materials for hydrogen production continue to evolve, driven by advancements in materials science, catalysis, and energy conversion technologies. The development of durable, cost-effective, and scalable materials coupled with their seamless integration into large-scale production systems holds great promise for unlocking the full potential of hydrogen as a clean and sustainable energy source. Continued research, innovation, and collaboration across multidisciplinary fields are essential to accelerate the development and deployment of cutting-edge materials for hydrogen production, contributing to a greener and more sustainable future.

Declaration of Competing Interest

The authors declare no conflict of interest regarding the publication of this article. The content and findings presented in this paper are based on objective research, scientific evidence, and the authors' expertise in the field. There are no financial, professional, or personal relationships that could potentially bias the content or interpretation of the information presented. The authors have no affiliations with organizations or entities that may have a vested interest in the subject matter discussed. This declaration ensures the integrity and impartiality of the information provided in this review article.

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