New and emerging applications of hydrogen including industrial, medical, and warfare applications

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Yusuf Oloruntoyin Ayipo[1,2], *Kabir Opeyemi Otun*[2,3], *Akeem Adebayo Jimoh*[2], *Mohd Nizam Mordi*[1]

[1]Centre for Drug Research, Universiti Sains Malaysia, Gelugor, Malaysia, [2]Department of Chemistry and Industrial Chemistry, Kwara State University, Malete, Ilorin, Nigeria, [3]Department of Physics, Institute of Applied Materials, University of Pretoria, Hatfield, Pretoria, South Africa

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1 Introduction

The world human population is estimated to cross 9 billion by 2050, considering the current rate of expansion, consequently amplifying the energy demand for domestic and industrial applications. To meet these needs, more than 36 billion tons of CO_2 (mostly from fossil fuels) are being released annually to the atmosphere due to the explorations for energy production. Worrisomely, the alarming rates have been anticipated to steeply increase in the coming years [1]. In addition to the scary consequential carbon emission, the fossil fuel natural reserves, especially petroleum, could become depleted rapidly in the near future due to its overreliance worldwide [2]. Thus, sustainable energy development such as renewable energy, clean energy carriers, and storage that could aid "zero-carbon" policy are necessarily required for economic and environmental viability worldwide [1].

Hydrogen (H_2) is recognized as the most abundant element in nature and the lightest owing to the unity number of electron, neutron, and proton in its atom [3]. It is considered as an excellent and clean fuel, and energy source, by some scientists [4] while to others, it is not a source of energy but a highly efficient energy carrier. It has attracted enormous applications in several fields, making it highly beneficial to circular economies [5]. Hydrogen has been forecasted to replace natural gases as a more efficient and cleaner energy carrier [6]. Its potential for inexhaustibility makes it an important promoter of new global economic vision, devoid of pollution and supporting waste management [5]. The recent developments of H_2 for green life provides opportunities for a significant reduction in pollutant emissions and promotes low-carbon society, major issues constituting the climatic and environmental challenges focused in the G20 summit 2018–19 [7].

Unlike the fossil fuel energy sources such as petroleum that are mostly associated with carbon-based pollutants, H_2 represents a promising energy source alternative with a cleaner combustion product (water) supporting long-term energy availability and green environment sustainability [2]. As such, the production of affordable, clean, and efficient H_2 could primarily actualize the desired transition to a carbon-

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free world [8]. Other advantages of H_2 utilization for energy production include efficient conversion into energy and other fuels, easy accessibility and affordability, a highly resilient system of energy, cleaner industrial productions, abundance and safety of production sources such as water and other renewable resources, zero-carbon emission, and sufficient heating value [8,9]. Additionally, H_2 has been shown to be potentially deployable to medical and biomedical fields where its application could notably support diagnosis, prevention, and treatment of human diseases/disorders, interestingly with ideal safety profiles. Similarly, the design of warfare tools and equipment such as hydrogen sulfide, hydrogen cyanide, hydrogen bombs, hydrogen ships, and thermonuclear reactors have been facilitated by the use of H_2. The invaluable contributions of H_2 to economic and technological advancement for human well-being require a regular overview.

According to the International Energy Agency (IEA), the global utilization of H_2 reached 95 Mt in 2022 from the 91 Mt and 94 Mt recorded in 2019 and 2021 respectively [10]. The rate is ideally expected to increase in 2023 considering the consistent 3% increase in yearly demand [11]. Thus, the global demand has been forecasted as 145 Mt and 600 Mt by 2030 and 2050, respectively [12]. Whereas, the current production rates for low-emission H_2 is significantly lower than the demand. Although, the production could rise to 38 Mt if all the potential projects in pipelines become realities, accordingly (International Energy Agency, 2022). Still, more efficient production technology needs to be developed for expanding the means to meeting its demand globally.

Therefore, this chapter reveals new and emerging diverse methods of production and applications of H_2 that have been explored in recent times through series of scientific and technological advances. It provides opportunities for expanding the scope of efficient, cost-effective, and safe approaches for the production and utilization of hydrogen for global developmental sustainability.

2 Production of hydrogen

The source of hydrogen is crucial to the hydrogen energy system, and this has formed the basis of ongoing research in this field [13]. The global production of hydrogen has been increasing rapidly on an annual basis for several years due to population explosion and ever-increasing energy demand. Almost 50% of the hydrogen produced is employed in ammonia synthesis, while the rest found their uses in the production of methanol, hydrocracking, and hydrodesulfurization of oil, among others [14]. The cleanness, efficiency, and cost-effectiveness of any hydrogen production pathway can be determined by the technologies used to produce hydrogen, which also affects the pathway's viability. Three components must be present for the production pathway to function properly: a material containing hydrogen from a hydrocarbon or nonhydrocarbon source, a source of energy as well a catalyst. Thus, the type of material used as a feedstock to extract hydrogen, the production level, and the availability of resources all affect the choice of hydrogen production. Hydrogen

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can be sourced from various resources including water, biomass, coal, fossil fuels, natural gas, and nuclear energy [4,14].

2.1 Water as a source of hydrogen production

The natural hydrosphere contains the greatest hydrogen in the form of water. Considering this, producing hydrogen, an affordable raw material such as water, is a difficult but crucial undertaking that could meet the world's energy demand. Free energy or high temperatures are necessary to split water to produce water. Free energy can be produced using solar energy (photolysis) and direct current, or it can be converted into heat or electricity [15]. Different processes for producing hydrogen from water include direct electrolysis [16], thermolysis [17], and thermochemical process [18].

2.1.1 Direct electrolysis

Here, an electrolytic cell is employed to split water into H_2 and oxygen. Direct electric current is allowed to flow between the two electrodes of the cell. The anode releases oxygen, while the cathode releases hydrogen. Alternate electrodes are encircled by diaphragms that stop gas from getting into the other electrode compartments [16]. Through this process, high efficiency, and improved performance at greater temperatures and pressures, the process straightforwardly offers H_2 and O_2. This is considered a clean method of hydrogen production if the electricity used is generated from renewable sources like wind or solar power. It is also known as “green hydrogen” when produced using renewable energy [19].

The electrochemical reaction that takes place during electrolysis, which results in the production of extremely pure hydrogen, is given below:

$$\text{Cathode: } 4H_2O + 4e^- \rightarrow 2H_2 + 4OH^-$$

$$\text{Anode: } 4OH^- \rightarrow 2H_2O + O_2 + 4e^-$$

$$H_2O + \text{electricity} \rightarrow H_2 + \tfrac{1}{2}\, O_2 + \text{heat}$$

2.1.2 Thermolysis

In the direct heat method, steam is produced by heating water to a temperature above 2500 K at which point it breaks into H_2 and O_2 gas. Hydrogen and oxygen must be kept apart from one another at this extremely high temperature because, as they cool, they will join once more to produce water [20]. This method minimizes environmental hazards and exhibits high thermal efficiency but high temperature requirements limit its practical applications. The separation of H_2 and O_2 in this industrial process is one of its difficulties. At temperatures as high as 2500 K, semi-permeable mem-

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branes currently on the market can be employed. Therefore, before beginning the separation process, the mixture must be chilled. In the work of Baykara, about 90% of the equilibrium was reached in solar thermolysis of water with a residence time and temperature of 1 ms and 2500 K, respectively. The findings further demonstrate that hydrogen can be conveniently separated from O_2 if the resulting gases are quickly cooled to 1500–2000 K and palladium membranes are employed [17].

2.1.3 Thermochemical process

Certain thermochemical processes, such as sulfur-iodine or copper-chlorine cycles, use high-temperature chemical reactions to split water into hydrogen and oxygen [18]. The fact that the individual chemical processes in the thermochemical process demand no catalyst is a significant advantage. All the chemicals utilized in the thermochemical cycle can be recycled, except for water, which serves as the raw material to produce H_2. The absence of O_2–H_2 membranes, the suitable temperature range of less than 1200 K, and the absence of minimal electricity consumption are further benefits of thermochemical water-splitting cycles [18].

2.2 Solar energy

The energy that comes from the sun is a clean and sustainable energy resource that can serve as a potential replacement for fossil-based fuels for future use. When solar energy is combined with water to create hydrogen, it creates an endless supply of usable primary energy that can be transported [21]. Light-based approaches through photoelectrochemical cells, photocatalysis, and photovoltaic (PV) electrolysis have been reported by the Clean Energy Research Laboratory (CERL) as economical and efficient methods for H_2 production [8].

2.2.1 Photolysis

Hydrogen can be generated when water molecules absorb energy from ultraviolet radiation. To release the formed gases, some photocatalytic materials are utilized to absorb visible light and transmit the energy of the water molecules at the proper wavelengths and intensities. Apart from the advantage that this method is direct and uses ordinary light, the photocatalyst can be recycled [22].

2.2.2 Photoelectrochemical process

This is a process that combines solar cells and water electrolysis in a single electrochemical cell, like the hole pairs in semiconductors [23]. Hydrogen is produced from water with the aid of sunlight and specialized semiconductors known as photocatalysts, which use light energy to split H_2O into H_2 and O_2. This process can reduce CO_2 emissions and for high conversion efficiency using affordable thin-film or particle semiconductor materials [24].

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2.2.3 Photovoltaic-electrolysis system

The sunlight is directly converted into power by a photovoltaic cell. A photo electrolyzer is a device that produces hydrogen by combining a solar cell and an electrolyzer. When the photoelectrolyzer is submerged in H_2O and exposed to sunlight, H_2 is produced. After that, the hydrogen is gathered and kept. Hydro, wind, wave, tidal, ocean thermal, and geothermal energy can all be employed as sources of electricity for onward application in electrolysis to produce hydrogen [25].

2.3 Hydrogen production from fossil fuels and carbon capture storage

Over 90% of the hydrogen in use today is sourced from fossil fuels. Coal, gasoline, methanol, natural gas, and other fossil fuels are used in this regard [26]. From the natural gas source, gray H_2 is produced from steam reforming of methane, blue H_2 from carbon capture and storage (CCS), while H_2 from catalytic solar thermochemical splitting of water and aquamarine H_2 is produced from carbon-catalyzed solar thermochemical pyrolysis of methane [27].

2.3.1 Natural gas reforming

This is the most frequently used method to produce hydrogen worldwide. It involves the conversion of natural gas into hydrogen and CO_2 via a process known as steam methane reforming (SMR) [28]. The resulting hydrogen is typically used in industrial applications. SMR is the most popular process in the chemical and petrochemical industries. It is also currently the most affordable way to produce hydrogen and generates the least CO_2 emission of all the fossil fuel production methods. SMR is highly endothermic and is expressed below [29]:

$$H_2O + CH_4 \rightarrow CO + 3H_2$$

2.3.2 Coal gasification

Coal can be gasified to produce a mixture of CO and H_2 (syngas), which can be processed to extract hydrogen. However, this process is less environmentally friendly than other methods due to the release of CO_2 and other emerging pollutants [30]. In large-scale plants, coal is an inexpensive and technically viable choice for producing hydrogen. Gasification is a more suited process than the currently used ones (such as electrolysis) for turning coal into hydrogen. The hydrogen output of these syngas is increased using a water gas shift process. Despite these benefits, coal gasification produces more CO_2 than other known technologies for producing hydrogen because of the high carbon content of coal. Technologies to capture and store carbon emissions are being explored to get rid of this problem. Coal gasification now costs more to produce hydrogen than natural gas steam reforming does [31].

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2.4 Hydrogen production from biomass

2.4.1 Biomass gasification

Biomass such as agricultural residues, or municipal solid waste, can be gasified to produce a mixture of gases, including H_2 [32]. This process involves heating the biomass in a confined environment and a limited supply of O_2, resulting in the production of syngas (CO and H_2). The hydrogen can then be separated from the syngas. When compared to combustion, gasification prevents the emission of many pollutants such as NOx, SOx, and other particulates that happen at temperatures above typical gasification temperatures [33].

Since moisture present in the biomass must also be evaporated, the gasification process normally has a low thermal efficiency. It can be done in a fixed bed or fluidized bed reactor and with or without a catalyst. The fluidized bed reactor often produces superior performance. When steam and/or oxygen are added to the gasification process, steam reforming occurs, producing a syngas stream with H_2 to CO in the ratio of 2:1 that can be fed into a Fischer–Tropsch reactor to produce higher hydrocarbons or via a water–gas shift (WGS) reaction to produce H_2. Fig. 10.1 is a scheme illustrating hydrogen production via gasification of biomass [34].

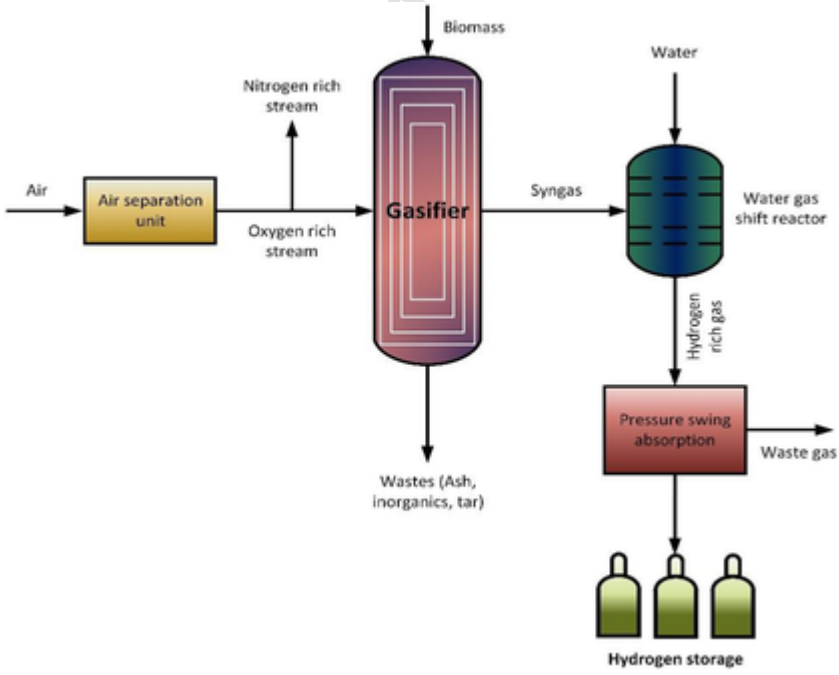


Figure 10.1 A scheme showing biomass gasification to produce hydrogen.
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2.5 Biological method of hydrogen production

Hydrogen is a by-product of the metabolic processes of several organisms, including bacteria and algae [35]. These mechanisms are physiologically separating the water into its constituent elements because they typically reside in water. Biological hydrogen production includes, but is not limited to the following:

2.5.1 Microbial hydrogen production

Some microorganisms, such as certain bacteria and algae, can serve as a source of hydrogen via biological means. For instance, H_2 has been reportedly produced from microflora such as *Opuntia imbricata* [36]. This is an area of ongoing research for sustainable hydrogen production. Biophotolysis of water, microbial electrolysis, and photo- and dark fermentation, all fall under this relatively new category, biological production. With the help of sunlight, certain microorganisms including cyanobacteria and green algae use biophotolysis to consume water and split it into hydrogen [37]. In biophotolysis, unique microorganisms like cyanobacteria and green algae make H_2 by consuming and dividing H_2O as part of their normal metabolic activities under the influence of sunlight. When exposed to light near IR, photosynthetic bacteria begin to photodegrade organic compounds. Purple bacteria, which have no sulfur content, can then use a specialized enzyme to convert the organic material into hydrogen. Anaerobic bacteria may degrade organic material in a dark environment to produce H_2 and other products. On the other hand, in microbial electrolysis, a weak voltage is generated at the anode when the bacteria break down organic matter. At the cathode, hydrogen is produced. In general, more energy is needed. Hybrid bio-H_2 systems are integrated systems that produce hydrogen with leftovers from one method as inputs to another. Low-light conversion efficiencies are a major barrier to the development of light-driven biohydrogen processes like biophotolysis and photofermentation. Yields are constrained by metabolic pathways in dark fermentative processes. Since increased yields require a supply of excess power, microbial electrolysis is not sustainable. To enhance the efficiency of biohydrogen processes, hybrid systems are taken into consideration [38].

2.5.2 Microbial electrolytic cell

Biodegradable materials are directly converted into hydrogen via electrohydrogenesis in microbial-aided electrolysis cells (MEC), also known as bioelectrochemically assisted microbial reactors (BEAMR). Exoelectrogens (special microorganisms) in a microbial fuel cell break down organic matter and facilitate the transfer of electrons to anode [37]. After passing through an external load and arriving at the cathode, the electrons mix with the protons and O_2 to produce H_2O. No oxygen is present at the cathode while an MEC functions, therefore an external voltage is provided to the cell rather than being produced by it. Since acetate substrate breakdown is not spontaneous under typical conditions, more energy is required. The cathode produces hy-

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drogen using Eq.

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

2.6 Multistage integrated process

To maximize the hydrogen production from the feed, a multistage process has been put in place. The procedure originally had two stages: dark fermentation and then photo fermentation, but three or even four stages have since been suggested in various arrangements [39]. In this procedure, the biomass material is initially added to a reactor for dark fermentation, where the bacteria break down the feedstock to produce hydrogen and effluent that is rich in organic acids. The difficulty of creating a source of organic acids for the photo-fermentative process is removed because the effluent contains organic acids.

The overviewed new and emerging approaches for the production of hydrogen are briefly summarized and illustrated in Fig. 10.2 and Table 10.1.

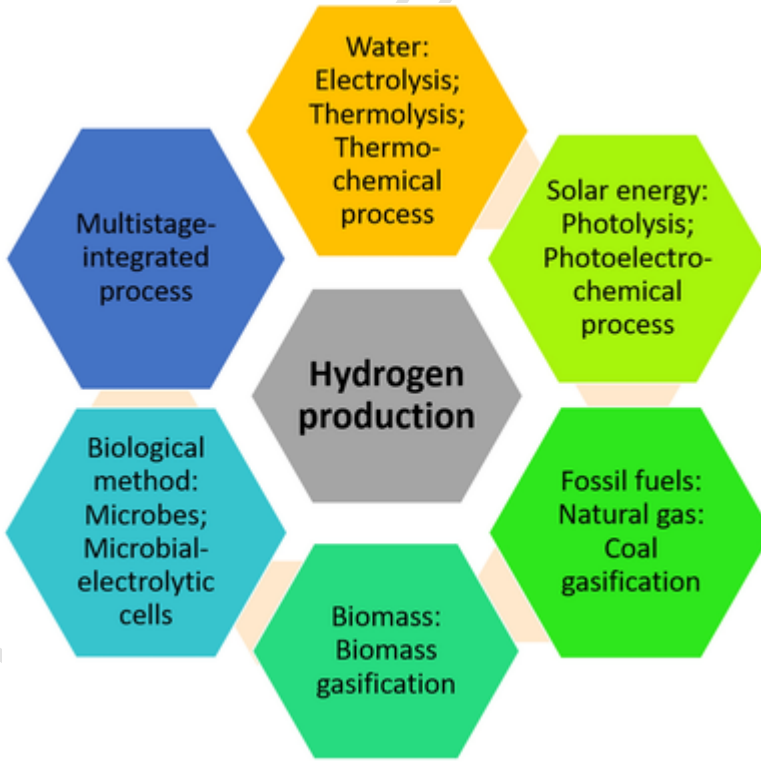


Figure 10.2 New and emerging methods of hydrogen production.

Table 10.1 Merits and drawbacks of selected hydrogen production systems.

System	Merits	Drawbacks	References
Biological	Possibly substantial resources	Finding the best biological organism for optimum production and commercial-scale production requires thorough research because of the slow hydrogen generation, the necessity for a lot of space, and other factors.	[40,41]
Electrical	Commercial accessibility, tested technology, an understandable manufacturing process, modularity, extremely pure production, suitability for both stationary and mobile needs, as well as commercial availability	Competition from renewable or green electricity	[16]
Photonic	Environmentally friendly technique, abundant source, minimal health risk, high efficacy, used on both small and big scales, and mobile or stationary	To develop new materials for solar energy that are both efficient and inexpensive, expensive, ground-breaking research is required.	[42,43]
Thermal	Low price, suitable for mass production, less harmful to the environment, and able to utilize industrial waste heat	To create materials that are resistant to corrosion and heat, research is required.	[44]
Nuclear	It reduced carbon emission	It raises significant environmental and health risks due to uranium mining and processing, the possibility of accidents, and the management and disposal of radioactive waste.	[45]

3 New and emerging applications of hydrogen

Hydrogen has an extensive spectrum of industrial applications due to its unique properties such as high energy density, flammability, and its ability to react with various substances [20]. As efforts to decarbonize industries and lessen greenhouse gas emissions grow, the use of hydrogen as a clean energy carrier and feedstock in industrial processes is expected to expand, particularly in the form of "green hydrogen" produced using renewable energy sources [46]. This includes steel production, where hydrogen is being explored as a potential substitute for coal. Making concrete, a

process that consumes a lot of energy and produces a lot of carbon, is another potential new application that could be explored. The usage of clean hydrogen in various industries today is briefly summarized below, along with several fascinating new disciplines that are looking into using hydrogen in industrial processes [22].

3.1 Industrial applications

3.1.1 Ammonia production

The Haber-Bosch process, which makes use of H_2 as a key component, is used to produce ammonia [47]. This process generates 180 megatons of NH_3 annually, of which 80% is utilized to make fertilizers. The demand for ammonia from current users is predicted to be unchanged or only slightly increased due to the rising demand caused by sophisticated applications. Future zero-carbon energy prospects are anticipated to heavily rely on wind and solar energy. Since the ammonia industry now accounts for 1.8% of global CO_2 emissions, there is a sizable window of opportunity for global carbon emissions reduction. This can be achieved through carbon capture, utilization, and storage (CCUS). Ammonia has the potential to serve as a storage media for hydrogen because of its ease of transportation when compared to hydrogen. As a result, initiatives that produce clean ammonia have begun to receive a lot of attention and investment [48].

3.1.2 Methanol production

With a consumption rate of 130 kg H_2/t, methanol production comes in second among industrial hydrogen uses. Methanol can be used for a variety of things, including paints, polymers, and explosives. The demand for plastics derived from renewable resources will surely increase if this trend persists. Multiple fuel uses, such as methyl-tert-butyl ether, are necessary either before or after formaldehyde conversion. According to estimates, the 100 Mt of methanol produced globally meets 25% of the needs of the chemical industry and 28% of the industrial hydrogen usage. Emissions can be decreased by replacing dirty hydrogen in the hydrogenation process. Researchers are also investigating how methanol manufacturing could aid in lowering atmospheric pollutants. Apart from the use of methanol as a chemical feedstock, it is also an alternative fuel for cars due to its fuel economy and ability to lessen greenhouse gas emissions [49].

3.1.3 Food industry

In the food industry, hydrogen is used for hydrogenation processes to convert unsaturated vegetable oils into more stable saturated fats, resulting in products like margarine. As such, hydrogen can be used in the packaging industry for the hydrogenation of oils and fats to create hydrogenated fats for use in food products, such as baked goods and confections [50].

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3.1.4 Metal refining

Hydrogen is employed in the refining of metals, especially in the production of high-purity metals. It can be used to reduce metal ores and remove impurities, resulting in higher-quality products [50].

3.1.5 Energy generation

Hydrogen is a versatile element with numerous potential energy uses, such as in residential power-supply units, zero-pollution vehicles, and electricity generation [51]. It possesses the capability to be efficiently converted into electrical energy via fuel cells, which stand out for their quiet and environmentally friendly attributes when compared to other established technologies [52]. This adaptability of hydrogen positions it as a strong candidate for deployment in various sectors, including transportation, electricity generation, and commercial and industrial applications. Nevertheless, it remains imperative to emphasize the necessity for safety precautions, given hydrogen's explosive nature, which can present substantial hazards [53,54]. Given its considerable promise as a clean energy source, the significance of safety measures in the transportation and storage of hydrogen cannot be overstated. Furthermore, the exploration of hydrogen's utility as a fuel source for heating, power generation, and cooking has also gained traction, owing to its remarkable versatility [55]. Hydrogen is an integral part of hydrogen fuel cells and as such can be used as a fuel in industrial power generation. This is particularly valuable in remote locations or areas where grid electricity is unreliable [50].

3.1.6 Electronics and semiconductor manufacturing

Hydrogen is used in the production of semiconductors and other electronic components. It is employed for cleaning and annealing purposes to ensure high-quality semiconductor materials [50].

3.1.7 Transportation

Forklift trucks, trains, and buses are a few examples of long-distance transportation. Due to significant price drops in Li-ion batteries and ongoing improvements in battery energy density and charging times, electric cars can compete with hydrogen across a broader range of lengths and scopes. This is especially advantageous for marketing plans and distribution avenues for this product that offer overnight charging capabilities. As a long-term backup, sustainable hydrogen alternatives may be preferable to more expensive diesel engines [50].

3.1.8 Oil refining

The oil refining sector was the largest single user of hydrogen in 2020 (almost 40 Mt H_2). In refineries, hydrogen is utilized to remove impurities (especially sulfur) and

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enhance the composition of heavy oil to produce lightweight goods. Hydrogen is used in the oil sector for hydrocracking and hydrodesulfurization processes. These processes help refine and upgrade crude oil into valuable products such as diesel, jet fuel, gasoline, diesel, etc. In the medium to long term, its use will diminish as there is a lesser demand for fossil-based fuels declines, notably in the transportation sector [56].

3.1.9 Plastics and other chemicals

Hydrogen may be utilized in cutting-edge processes for making chemicals and plastics, such as methanol to aromatics and methanol to olefins. Since these techniques require the utilization of long-term CO_2 sources, such as those produced from sustainable biomass or direct air capture, using a more sustainable feedstock may result in more effective decarbonization solutions [50].

3.2 Medical and biomedical applications

3.2.1 Diagnosis of gastrointestinal diseases and disorders

Accordingly, molecular H_2 has been effectively applied as an aseptic agent and for detecting internal body wounds such as the wound in the gastrointestinal (GI) tract during the Millennial generation [57,58]. Recently, the H_2 breath test (HBT) has become a popular diagnostic technique for monitoring the syndromes of carbohydrate malabsorption/maldigestion and small intestinal bacterial overgrowth (SIBO), pathophysiological conditions of GI disorders. Subcategories of HBT include the fructose HBT and lactose HBT for observing fructose and lactose malabsorption, respectively. Others include glucose HBT and lactulose HBT (LHBT), both for diagnosing SIBOs, while LHBT is also widely applied for monitoring the condition of orocecal transit time (OCTT) for GI motility and sensitivity [59,60]. Interestingly, research activities have proved the technique to be economical, safe, and simple to operate for the diagnosis of common GI diseases and disorders [60,61].

3.2.2 Pharmaceutics and therapeutics

The pharmaceutical industry also makes extensive use of hydrogen, using it to produce specific drugs. Hydrogen can be used to produce hydrochloric acid, hydrogen peroxide, and table sugar, all of which are useful in the pharmaceutical sector [50]. Hydrogen peroxide, H_2O_2 is a clear liquid that is used frequently in the pharmaceutical industry as a crucial chemical and oxidant. Medical sciences are paying more and more attention to the utilization of hydrogen as a healing medicinal gas. Among the other known medicinal uses of hydrogen are the treatment of arthritis, diabetes mellitus, neurological diseases, and cancer, among others.

According to a recent report by Yuan and co-workers, the interesting reducing property of H_2 facilitates its selective antioxidant effects. These inclusively occur through a direct reaction with cellular free radicals, including the hydroxyl, nitrosyl, and peroxy free radicals, thereby preventing the chains of biomolecular destructions.

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Such active therapeutic pathways, synergistically with the endogenous antioxidants prevent oxidative stress, inflammation, fibrosis, and cell apoptosis, and are amenable to medical and biomedical applications. It has also been revealed that H_2 interacts with several organs relevant to ischemia and reperfusion injury. As such, it induces protective activities against various diseases, including bone and joint diseases, neurodegenerative diseases, and respiratory diseases. More impressively, it has not been reported to engender any significant interruptive effects on the normal metabolic redox pathways since it readily diffuses into cells and tissues, thereby assuring its systemic safety [62,63]. Other studies have also suggested that prolonged inhalation of H_2 is tolerated to a large extent, supporting its safety for medical and biomedical applications and dousing the concern of environmental exposure. However, further effects on cardiac arrests are recommended for further studies [64].

In addition to the diverse industrial applications, the versatility of H_2 has expanded to medical and biomedical applications, where it has been employed to mitigate various diseases affecting humans [65]. The strong reducing effects of H_2 and H_2-containing biomedical agents (e.g., oxygen and water) have promoted its antioxidant activities, amenable to suppressing the prognosis of various human diseases. For instance, H_2-rich water reportedly attenuates the blood's total antioxidants [66]. Several reports have also revealed its protective and curative potential in molecular or combined forms against various diseases and ailments [67,68] including oxidative stress, cellular apoptosis, cartilage damage [67], autophagy [69], cardiovascular diseases [69,70], central nervous system disorders [69], traumatic brain injury [71], ocular diseases [72], metabolic syndromes [73], coronavirus 2019 (COVID-19) and its comorbidities [74], and aging and associated diseases [75]. Molecular H_2 has also been overviewed as a promising antitumor [76], inclusively through the suppression of peroxide, thereby mitigating hydroxyl-radical-induced cellular damage and senescence [77] and other oxidative stress agents. However, the major drawback remains the design of an efficient release system for its adequate supply to the organs [62]. Nevertheless, the application of H_2 advances the development of affordable, efficient, effective, and safe medical approaches for preventing and treating human diseases and disorders. The emerging application trend thus, deserves further scientific exploration.

3.3 Hydrogen applications in warfare

Hydrogen is the most abundant element in the universe and holds great potential as a source of energy. However, beyond its industrial and energy applications, hydrogen has also been a subject of interest for military purposes [78]. While hydrogen has many beneficial properties, its potential as a weapon of war should not be overlooked. Hydrogen has a low ignition energy and burns with an invisible flame, making it difficult to detect [79]. Furthermore, hydrogen combustion can produce a great deal of heat and energy, making it highly explosive when combined with oxygen. In the context of warfare, hydrogen has been used as a component in incendiary bombs since World War I. Hydrogen-filled balloons were also deployed as surveillance or

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reconnaissance equipment and to conduct bombings, such as the V-1 flying bomb used by Nazi Germany during World War II [80].

The chemical properties of hydrogen have also been exploited to produce hydrogen sulfide, a toxic gas used as a chemical weapon during World War I. The Department of Homeland Security is concerned about the potential misuse of hydrogen sulfide as a weapon of mass destruction due to its neurotoxicity. Moreover, hydrogen cyanide was another chemical produced using hydrogen and deployed as a chemical weapon during World War I and, to a lesser extent, during World War II [81]. Its rapid diffusion and high vapor pressure limited its effectiveness as a chemical weapon, but it still resulted in the procurement and sea disposal of significant quantities of hydrogen cyanide by the United States during World War II. It is important to note that while hydrogen has been used in warfare, its potential as a fuel of the future for clean energy applications should not be overshadowed [82]. Apart from its potential applications in warfare, the chemical properties of hydrogen also make it a promising source of energy with several beneficial characteristics [19].

3.3.1 Hydrogen in warfare: historical context

Throughout history, hydrogen has played significant roles in warfare, serving as a crucial component in explosives and as fuel for volatile devices. One notable instance was during the Napoleonic wars in the late 18th and early 19th centuries, where hydrogen-filled balloons were instrumental in reconnaissance efforts, providing an elevated vantage point for monitoring enemy positions and maneuvers [83].

During the Civil War, hydrogen-filled airships, often known as zeppelins, found utility among both Union Army units and Confederate forces for reconnaissance and bombing missions. Nevertheless, the inherent flammability of hydrogen made these airships vulnerable to enemy attacks, leading to the downing of numerous airships during the war. Surprisingly, despite the risks, the use of hydrogen persisted in airships during the interwar period, even expanding into civilian applications such as passenger travel [84].

Also, during World War I, German forces introduced hydrogen-filled artillery shells, commonly referred to as “fire balloons” or “drachen.” These munitions were engineered to release hydrogen and ignite upon impact, generating fires in enemy positions. Moving to World War II, the Japanese military pioneered the “fire balloon” or “Fu-Go” balloon bomb, which carried explosive payloads across the Pacific Ocean to the western coast of the United States. Despite these efforts, it was found that these devices were relatively ineffective in inflicting significant damage [84].

Hydrogen has been instrumental in the advancement of thermonuclear weaponry, commonly known as hydrogen bombs. These arms are extraordinarily potent, employing a fission bomb to trigger a fusion reaction, leading to the release of an enormous amount of energy. The United States achieved a successful test of a hydrogen bomb, designated “Ivy Mike,” on the Enewetak Atoll in the Pacific Ocean [85]. The Soviet Union likewise achieved a milestone with its inaugural hydrogen bomb trial, recognized as “RDS-6s” or “Joe-4,” in 1953. Presently, numerous nations include hydrogen bombs in their nuclear arsenals. The technology has seen substantial progress

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since its inception, with the development of more compact and intricate designs. Nonetheless, global initiatives like the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) strive to curb the proliferation of nuclear arms and advocate for the peaceful application of nuclear energy [86].

3.3.2 Applications of hydrogen in military technology

Hydrogen has found diverse applications within military technology, encompassing propulsion systems, and energy sources. It is reported that hydrogen fuel cells have been harnessed to supply power to a variety of military vehicles, spanning submarines, drones, and ground-based vehicles. These fuel cells present a clean and highly efficient substitute for conventional internal combustion engines. Furthermore, hydrogen serves as a propellant in certain missile and rocket systems, delivering a formidable energy-to-weight ratio that enables robust thrust capabilities [87]. Certain military submarines, especially those in non-nuclear-powered fleets, incorporate hydrogen fuel cells for generating electricity. These fuel cells offer a subdued and covert option compared to conventional diesel-electric systems. Additionally, there have been trials involving hydrogen as a potential fuel for aircraft engines. Experimental aircraft have been engineered to operate on hydrogen, and ongoing research is assessing its viability for broader military applications [88].

The military has deployed hydrogen as hydrogen fuel cells used for the generation of electricity in remote military installations or during field deployments where a reliable power source is needed as well as backup power sources for critical military infrastructure, ensuring continuity of operations in case of grid failures or other emergencies [89]. Hydrogen can also be used to store excess energy generated from renewable sources, allowing military installations to operate independently from the grid and can serve as a tool for improvisation of portable power sources for soldiers in the field, reducing the need for heavy and cumbersome battery packs [90].

Hydrogen can serve as explosives, though, not a primary use, it has been utilized in certain types of explosives, especially in combination with other compounds to enhance their destructive capabilities [91,92]. While hydrogen has significant potential in military applications, it's worth noting that there are logistical challenges associated with its production, storage, and transport. Additionally, safety considerations regarding the flammability of hydrogen need to be carefully addressed in military contexts [93]. The new and emerging applications of hydrogen are summarily illustrated in Fig. 10.3.

4 Limitations on hydrogen production, storage, and applications

Despite the numerous advantages of H_2 applicability, its safety profiles in terms of flammability (ability to ignite and explode) and material compatibility remain its major concerns [4,94]. Although, the application of solid-state systems for H_2 storage has quantitatively aided H_2 security for economic development, ameliorating the

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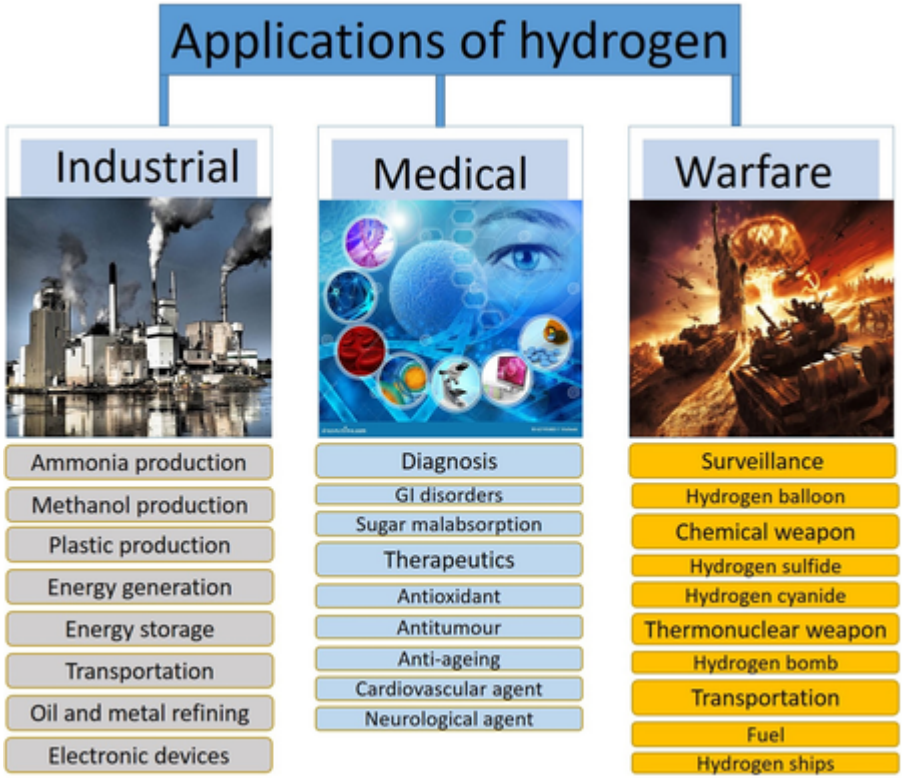


Figure 10.3 Summary of new and emerging applications of hydrogen.

storage challenges with the conventional gaseous state storage systems. However, the techno-economic realization of such storage systems needs to be advanced to overcome some associated drawbacks, including low storage capacity, high-temperature absorption/desorption and slow kinetics [95]. Moreover, its transportation in pure forms remains challenging [6]. In addition, the problem of carbon emissions from the fossil fuel route of "gray" hydrogen production has been bypassed by the introduction of the CCS system for "blue" hydrogen. However, the process of capturing and storing the CO_2 is quite expensive [27]. Progressively, the sufficiency of water preferentially favors blue H_2 economy by electrolysis. However, the technological development of the process still requires significant advancement and the expensive costs of high electricity demand remain a critical constraint [27,96,97]. Bezdek recently observed that the global preparation for the imminent H_2 economy is still primitive in terms of the labor market, and as such, requires further attention [98].

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4.1 Hazards and safety concerns in hydrogen warfare

Hydrogen warfare, specifically in the context of its use as a military weapon, presents several hazards and safety concerns. These arise from the highly flammable and explosive nature of hydrogen. Hydrogen is highly flammable in the presence of oxygen even at a very low concentration. Hydrogen in the air can be explosive if ignited, which can result in a wide flammable range (between 4% and 75% by volume in air), making it potentially dangerous in a variety of situations [99].

Hydrogen is the lightest and smallest molecule, which makes it prone to leakage through small gaps or cracks; therefore, proper ventilation and leak detection systems are crucial. It is typically stored under high pressure, which necessitates robust storage and transportation infrastructure to prevent leaks or ruptures. Liquid hydrogen is extremely cold (−253°C or −423°F) and requires specialized, well-insulated containers to prevent rapid evaporation (Najjar, 2019; Tashie-Lewis & Nnabuife, 2021). The high ignition potential of hydrogen necessitates strict safety measures. In areas where hydrogen is present, all electrical equipment must be explosion-proof. Additionally, meticulous grounding procedures are imperative to prevent ignition through static electricity or sparking from electrical equipment [100].

The incomplete combustion of hydrogen can produce pollutants such as nitrogen oxides (NOx), which have environmental and health impacts. Although hydrogen itself is a clean-burning fuel, the methods used for its production (e.g., SMR) can generate greenhouse gas emissions unless low-carbon production methods are employed. Proper training and awareness programs are crucial for personnel handling hydrogen to understand the hazards and safety protocols. Personnel working with or near hydrogen should have access to appropriate personal protective equipment (PPE), including flame-resistant clothing and safety goggles [101]. Moreover, the adoption of low-carbon production methods crucially offers more beneficial routes to mitigate these impacts [102,103]. Thus, proper training and awareness initiatives are essential for personnel involved in handling hydrogen. These programs equip individuals with the necessary knowledge of hazards and safety protocols associated with hydrogen. Personnel working close to hydrogen should have access to suitable personal protective equipment (PPE). This includes flame-resistant clothing and safety goggles, which are crucial safeguards in ensuring their well-being [104].

5 Conclusion and perspectives

It has been reiterated that H_2 possesses numerous applicability advantages for a wide range of industrial, domestic, and biomedical applications. However, the challenges of its regular supply and effective storage at economical rates remain primitively studied and deserve further scientific attention. Therefore, focusing on its sustainable routes of adequate supply through the new and emerging production advancement as herein revealed remains imperative. Currently, SMR of natural gas produces a substantial amount of H_2, but it also produces a significant quantity of CO_2 and other

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greenhouse gases. As a result, there are conscientious efforts to produce renewable hydrogen using different resources and methods. Water electrolysis, gasification of biomass, photocatalysis, biophotolysis, dark fermentation, photofermentation, and a few others are methods for producing hydrogen in this regard. Due to its numerous uses in fuel cells, upgrading of fuels, pharmaceutical industry, and the metalworking industry, to mention a few, the demand for hydrogen has been steadily rising in recent years. In the energy sector, and the manufacture of liquid fuels and higher alcohols, the application of H_2 has been demonstrated to offer more economical and safer alternatives. It is also used in oxy-hydrogen flames in the metallurgical field to cut and weld metals as well as reduce metals from solutions. Hydrogen can also be used for medical and biomedical applications, including disease diagnosis, prevention, and treatment as an imaging agent, anticancer, antioxidant, cardiovascular, and neurological agent, etc. Despite its safety in these regards as demonstrated in several experiments, the effects of prolonged exposure to it on various cardiac injuries require more comprehensive interventions. Moreover, the system for its regular supply and distribution to biological targets remains underdeveloped and therefore deserves more focus. Hydrogen remains an indispensable energy source and carrier for a wide range of industrial applications. It is potentially useful for disease management and is applicable for warfare technological development. All-in-all, the attainment of the Millennium Development Goals (MDGs) could be facilitated through the effective production and application of hydrogen, as emphasized in this chapter.

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Further reading

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