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Recent developments in the production of hydrogen: Efficiency comparison of different techniques, economic dimensions, challenges and environmental impacts

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ABSTRACT

Hydrogen (H_2) as a clean and environmentally-friendly carrier can be introduced as the fuel of future to mitigate the air pollution caused by industrial anthropogenic activities. With the aim of fulfilling the need of a green H_2 green production, disparate technological processes have been developed in current decades. Purposeful review of these H_2 production processes can allow the expert readers as well as non-expert readers to properly perceive the limitations and future perspectives for future research. H_2 may be manufactured from renewable or non-renewable energy sources. Despite significant advancements in the techniques of H_2 production, the emergence of various operational/technical challenges in obtaining a steady state and stable H_2 economy via increasing the process yield and decreasing production costs has motivated the researchers the study more to develop more efficient processes. Therefore, development of a scientific techno-economic analysis for all existed H_2 production techniques is of great importance to highlight the future perspective of this important energy source. The main objective of this paper is to comprehensively review the advantages and disadvantages of various H_2 production techniques. Moreover, the economic dimensions of each technique along with the role of nanotechnology in the production of H_2 are aimed to be reviewed in this paper.

1. Introduction

In recent decades, discovery of sustainable and eco-friendly fuels is an important challenge to meet the growing demand of energy all over the world [1–4]. Fossil fuels have long been applied as a cost-effective and versatile energy source but their major drawbacks such as the emission of detrimental greenhouse gases, acid rain and rapid depletion have significantly restricted their use in industry [5–9]. Therefore, finding novel clean and efficient energy sources is of great importance.

Hydrogen)H_2(is regarded as a scarce substance, which has noteworthy potential of application in disparate industrial-based activities including chemical, energy, metallurgy and food. Compared to

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prevalent types of fuels, H_2 enjoys some precious advantages such as very high value of energy per mass, clean combustion and safe transportation [10–12]. Due to the these brilliant positive points, H_2 has been recently considered as a promising fuel due to its great capability to be applied as an energy carrier and storage medium in fuel cells [13,14].

The recent report of Hydrogen Council (HC) denotes the fact that the overall expenditure of H_2 production and transportation is predicted to be declined up to 50% by 2030, which makes this environmentally-friendly fuel competitive with various conventional fossil fuels.

Moreover, HC reported that to reach an acceptable H_2 competitiveness, almost $70 billion is needed as investment support [15]. There are disparate techniques to produce H_2. Despite the production of almost 95% of H_2 from petroleum-based hydrocarbons, some attractive approaches such as electrolysis and thermolysis can be of great interest to manufacture renewable H_2 from disparate sorts of waste [16].

In recent years, electrolysis is the only commonly-applied technique for the manufacturing of renewable H_2 at commercial scale [17]. It is worth noting that the comparison of electricity and H_2 implies this reality that electricity has important shortcomings high-voltage-related heat losses and electrical resistance but H_2 possesses brilliant positive points like excellent efficiency of energy conversion, abundancy, high storage capacity and favorable heating value in comparison with conventional fossil fuels [3,14,18]. For instance, Jeon and Min investigated the production process of H_2 applying monolithic photovoltaic-electrolytic cell-based technique via concentrating on the water oxidation electrocatalysts and their preparation procedures. They corroborated that the mixture of electrolytic cell with photovoltaic can be considered as a trustworthy approach with high stability and efficacy [19]. Fig. 1 schematically presents different H_2 production routes from renewable sources.

Application of H_2 energy has recently been a promising alternative for fossil fuel and possesses great ability to meet almost 8% of global energy demand (GED) with a manufacturing value of 2.50 USD/kg. It is estimated that the H_2 manufacturing cost decreases to <1.80 USD/kg at

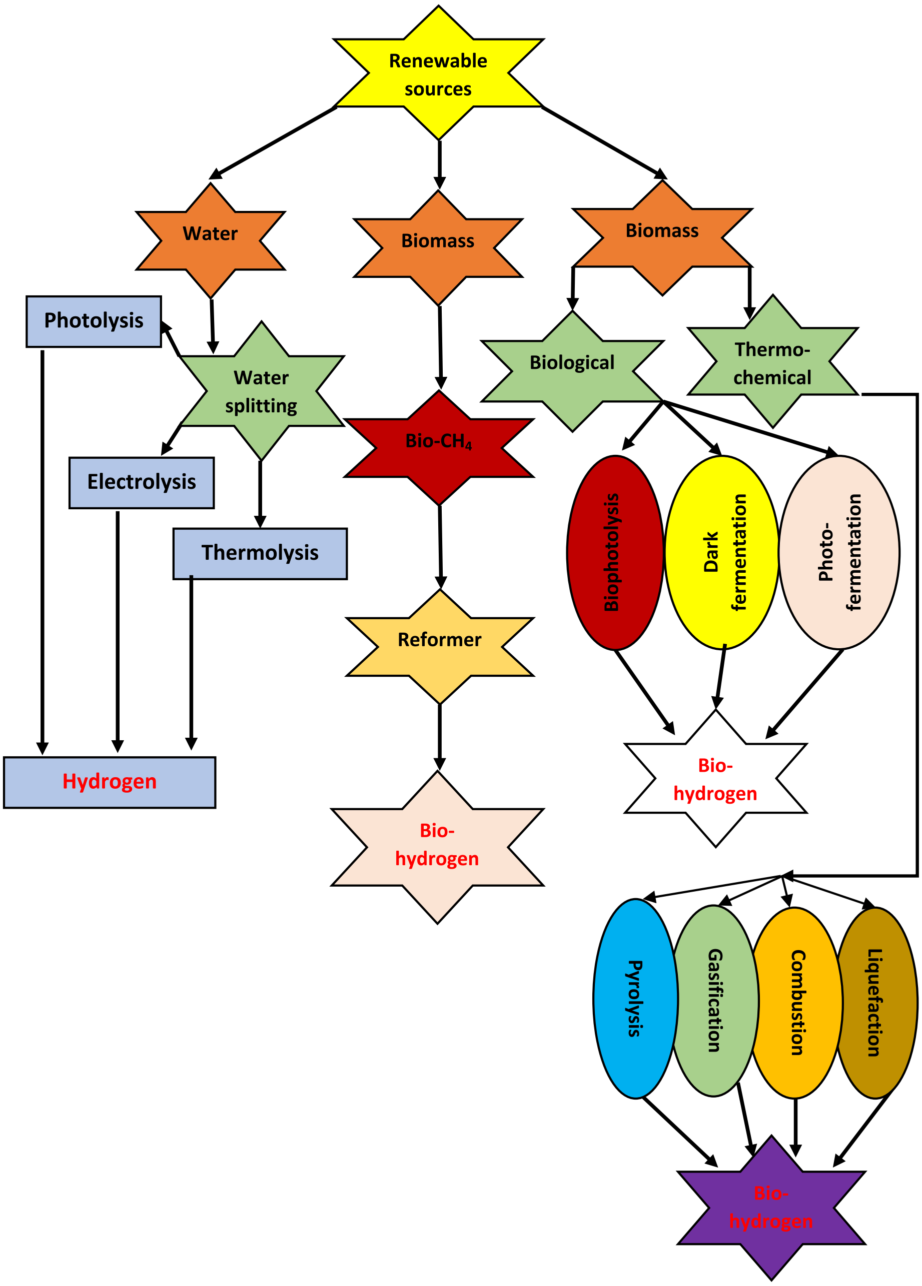

Fig. 1. Various H_2 production routes from renewable sources. Reprinted from [10] with permission from Elsevier.

the end of 2030 and also can meet nearly 15% of GED [20]. Based on the HC report in 2017, the amount of H_2 energy demand will go beyond 10 EJ/year by 2050 with 5 to 10% increment annually. In 2050, H_2 energy may be able to meet the GED by up to 18% [21]. The above-mentioned techno-economic investigation implies the fact that H_2 will indisputably have an important role in fulfilling the GED in the future due to having remarkable advantages including negligible production cost and low carbon content.

The term "H_2 economy", which was initially emerged in 1970, can be considered as a long-term purpose for disparate third-world countries to increase their energy security [22]. Fig. 2 schematically illustrates the global demand of H_2.

This paper aims to provide a comprehensive overview on the main properties of disparate H_2 production techniques and their associated advantages and disadvantages. Moreover, the techno-economic evaluation of each technique along with the role of nanotechnology in the production of H_2 are discussed in this paper, which results in providing an opportunity for the introduction of the most efficient and cost-effective technique for H_2 production.

2. Prevalent techniques of hydrogen production

2.1. Methanol steam reforming (MSR)

MSR can be considered as a commonly-employed process for converting hydrocarbons into H_2 because of its noteworthy positive points such as excellent efficacy and economic operation [23–25]. In comparison with oxidation processes, the MSR process can generate greater moles of H_2 for each mole of methanol. A schematic illustration of the MSR process is presented in Fig. 3.

Methanol decomposition (MD) and MSR reactions are respectively denoted by Eqs. 1 and 2 as follows [26]:

$$CH_3OH + H_2O \leftrightarrow CO_2 + 3H_2 \Delta H_{298} = +50\ kJmol^{-1} \tag{1}$$

$$CH_3OH \leftrightarrow CO + 2H_2 \Delta H_{298} = +91\ kJmol^{-1} \tag{2}$$

The prevalent application of Cu-based catalysts in MSR reaction is attributed to the application of similar catalyst in methanol synthesis [24].

In an investigation Yong et al. evaluated disparate mechanisms of MSR reaction based on Cu-based catalysts as follows [27]:

1) First mechanism: sequential trend of methanol decomposition accompanied by water gas shift reaction (WGSR). In this process, CO is treated an initial product. The existence of low value of CO is due to reaching WGSR to equilibrium [28].

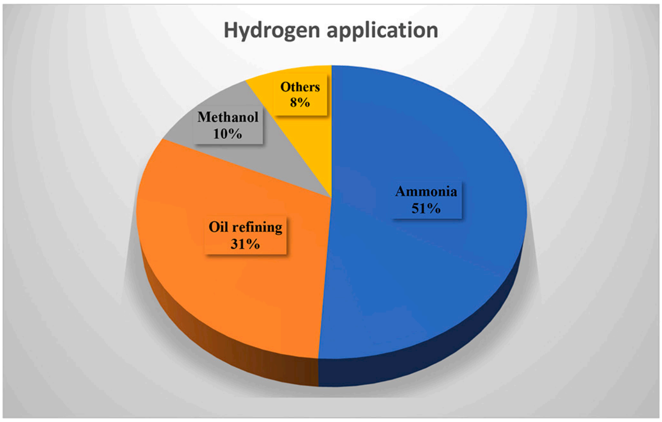

Fig. 2. Schematic demonstration of the H_2 global demand. Reprinted from [20] with permission from Elsevier.

2) Second mechanism: In this mechanism, at first Eq. 2 occurs and then after, Eq. 3 takes place as follows:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \Delta H_{298} = -41\ kJmol^{-1} \tag{3}$$

This mechanism recommends direct generation of products from methanol dehydrogenation.

2.2. Bio-Oil model molecules reforming

Regarding the thermal procedures, manufacturing of H_2 from biomass may follow two prominent routes including the gasification to achieve syngas and the pyrolysis to achieve bio-oil accompanied by reforming [29]. In comparison with biomass, bio-oil enjoys higher energy density. Bio-oil is known as the product of thermal pyrolysis, which consists of a blend of organics like alcohols, ketones, carboxylic acids, aldehydes, etc. [30]. In recent years, numerous investigations have been conducted to evaluate the efficiency of bio-oil model molecules. Comparative investigations on the steam reforming process of various organic molecules derived from bio-oil (i.e., methanol, formic acid, ethanol, acetic acid and furfural) have illustrated this reality that the molecular structures significantly affect the reactivity and propensity of coking through steam reforming process [29]. The stream reforming process of methanol and formic acid can be taken palace at lower temperature due to the non-existence of aliphatic carbons chain for cracking, while this process for ethanol, acetic acid and furfural needs greater temperature and produces considerable values of coke deposits particularly acetone and acetaldehyde. Fig. 4 schematically demonstrates the trend of coke formation per reactant molecule.

It is worth pointing out that the features of catalysts play an indisputable role in the coke formation mechanisms. Comparative analyses have implied that alumina support significantly affects the catalyst stability within the steam reforming process of methanol, acetic acid and acetone steam reforming [31]. The stability of unsupported Cu was less than Cu/Al_2O_3, while the unsupported Ni demonstrated greater stability compared to Ni/Al_2O_3. Apart from the formation of coke, the accessibility and renewability of feedstock is an important challenge. Various types of bio-alcohols like methanol and glycerol are conveniently obtained from renewable sources. Thus, they can be an appropriate alternative to natural gas [32].

2.3. Glycerol steam reforming (GSR)

Glycerol is known as a clean and promising energy source owing to its great potential to fulfill disparate social demands without detrimental impacts of fossil fuels [33,34]. Due to this reason, the GSR has been recently of paramount attention as an efficient process for H_2 production [34,35]. The conversion process of glycerol to H_2 through GSR is expressed by Eq. 4 [36]:

$$C_3H_8O_8 + H_2O \rightarrow 3CO_2 + 7H_2 \Delta H_{298} = 128\ kJmol^{-1} \tag{4}$$

The abovementioned equation is the combination of Eq. 3 and Eq. 5 [37]:

$$C_3H_8O_3 \rightarrow 3CO + 4H_2 \Delta H_{298} = 251\ kJmol^{-1} \tag{5}$$

Easy conduction of GSR at atmospheric pressure is the main advantage of this process. However, the requirement of a high-performance catalyst is still an important challenge of this process [38]. Disparate types of catalysts based on Ni, Pt, Co, and Ru have been currently under investigation. Among the studied catalysts, Ni-based catalysts are being extensively employed [39–42].

2.4. Gasification

Gasification can be defined as the conversion process of each carbon-based raw substance into synthetic gas applying air, steam or O_2

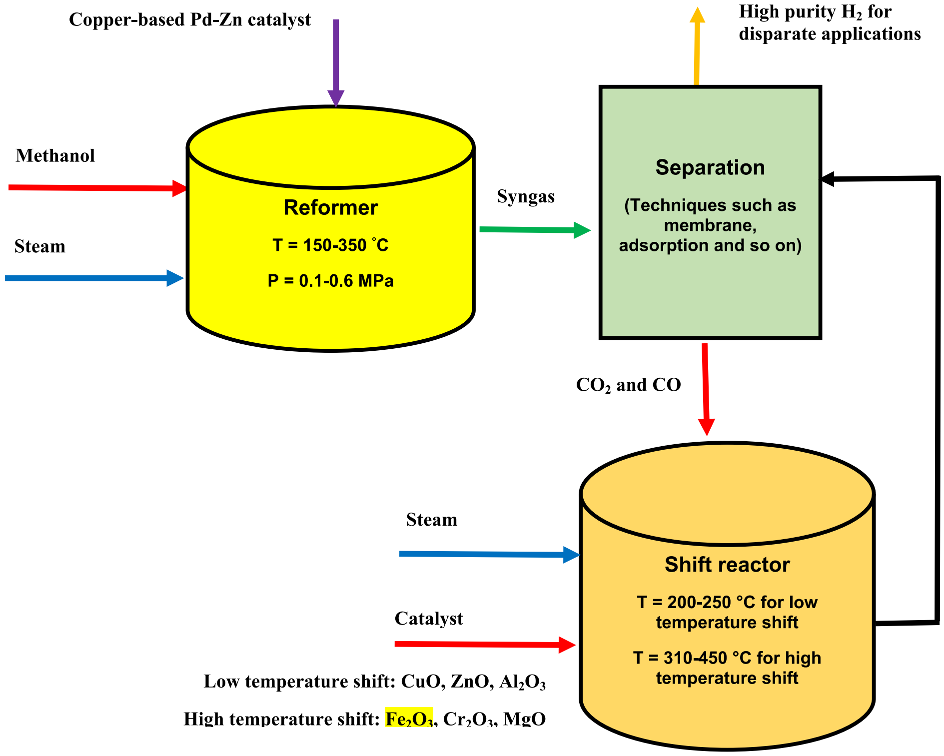

Fig. 3. Schematic demonstration of the MSR process. Reprintedfrom [26] with permission from Elsevier.

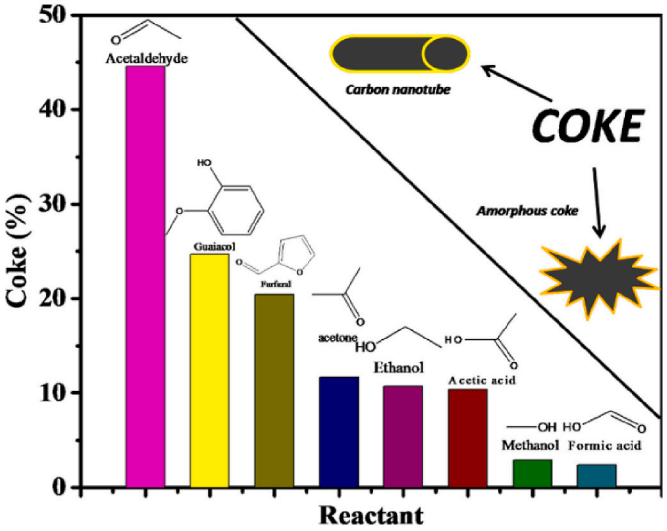

Fig. 4. Schematic demonstration of the trend of coke formation per reactant molecule. Reprinted from [29] with permission from Elsevier.

[43–45]. This process possesses great ability to convert numerous undesired materials like coal, sewage sludge, wood and plastic waste into beneficial outputs [46,47]. After gasification process, the purification of end products from contaminants using disparate types of gas clean-up processes is of great importance to increase their calorific value applying various gas clean-up processes [48]. Through the gasification process, four kinds of coal including lignite (low rank), sub-bituminous coal (low rank), bituminous coal (medium rank), and anthracites (high rank) are often applied in appropriate behavior [49,50].

Different techniques such as fixed-bed gasification, fluidized-bed gasification, moving-bed gasification and entrained-flow gasification are able to be used for the gasification of the above-mentioned coals at the temperatures >900 °C [49]. Among the aforementioned processes, the entrained-flow gasification of coal can be implemented at greater temperatures (1200–1700 °C), while other processes need temperatures <1200 °C [51,52]. Coal gasification is known as a promising and efficient process for the generation of more affordable and cleaner energy, which has shown its great potential to mitigate the emission of carbon into the atmosphere [53,54]. Plasma gasification is known as the most novel coal gasification procedure [53]. Owing to the operation of this process at high temperature, excellent conversion performance may be obtained. The products of the plasma gasification process are syngas and slag [55]. Compared to other gasification process, the plasma gasification process is more eco-friendly. The statistics show that the efficiency of plasma gasification process is 50% higher than combustion process, 43% higher than pyrolysis process and 19% higher than other gasification procedures [56]. Due to possessing high operating temperature, convenient recovery of waste metals via plasma gasification process is more possible than other gasification processes [57].

2.5. *Autothermal reforming of methanol (ATRM)*

ATRM can be realized as a commonly-employed H_2 production technique comprising of both partial oxidation and steam reforming reaction systems [58]. In this technique, the reaction of fuel with both air and steam occurs with the aim of producing H_2-rich gas. ATRM method applies adequate amount of heat produced from exothermic partial oxidation of methanol to accelerate endothermic methanol steam reforming with appropriate combination of air, steam and fuel. The operation of ATRM process takes place at thermoneutral point. At this point, neither consumption nor release of external energy takes place [59]. The occurrence of ATRM process at the thermoneutral point makes the fabrication of setups easier and significantly reduces the capital costs. In comparison with partial oxidation of methanol, ATRM process possesses superior heat recovery and H_2 production efficiency. In the general form, ATRM process is defined by Eqs. 6 and 7 [26].

$$CH_3OH + (1-2r)H_2O + rO_2 \leftrightarrow CO_2 + (3-2r)H_2 \tag{6}$$

$$\Delta H_{298} = (-241.8\,(2r) + 49.5\,)\,kJmol^{-1}, 0 \le \mathrm{r} \le 0.5 \tag{7}$$

In these equations, the ratio between oxygen and methanol fed is presented by r.

2.6. Photocatalytic method

Photocatalytic technique is known as a promising H_2 manufacturing process, which applies solar energy for the creation of electron-hole pairs via photons and semiconductors [60]. Sacrificial agents are used in this technique to separate photo-excited electron-hole pair. These agents permit H_2 formation with the re-combination of reduced electron-hole pair. Despite great performance and acceptable efficiency, this technique has recently encountered with some functional challenges for implementation applying visible light, which declines the efficiency of photon conversion [32,60].

With the aim of obtaining suitable photocatalytic water splitting, the employed photocatalysts ought to possess some momentous criteria including great ability to absorb visible light, excellent chemical stability under redox conditions, reasonable cost and appropriate adaptability for large-scale H_2 manufacturing processes. Therefore, development of high-performance photocatalysts with great photo-conversion efficacy is the major purpose for completing the photocatalytic H_2 evolution [61]. Disparate configurations such as NiS-based heterojunctions, TiO_2-based core–shell structures and imogolite hollow cylinders have been recently employed for photocatalytic H_2 evolution [32,61–63]. Among the above-mentioned configurations, the TiO_2-based core–shell structures have received more attentions owing to their remarkable properties including excellent chemical resistance, cost-effectiveness and availability [64]. Despite significant advancement on the design of novel photocatalysts with great efficiency, some important challenges are existed. For instance, the majority of metal chalcogenides-based heterojunctions are just able to split water in the existence of sacrificial agents [32].

2.7. Electrolysis of water

Electrolysis is the most commercially applied technique for H_2 production, which electrochemically divides water into H_2 and O_2 [65]. Among various approaches of electrolysis, grid electrolysis applies conventional electricity and thus, can improve the economy of H_2 production by decreasing the cost and increasing the rate of production [66]. Despite great efficiency and suitable cost-effectiveness, the emission of greenhouse gases is the prominent challenge of this technique. This important advantage can be solved via the application of wind electrolysis. In this method, the connection of electrolyzer to wind turbines causes the creation of electricity.

The emergence of more environmentally-friendly approaches of H_2 production, the emission of detrimental greenhouse gases has been considerably declined due to the share of clean energy to the electricity grid [67]. Apart from production cost, the storage and the transportation cost have indisputable role for the economic analysis of H_2 manufacturing process. Solar electrolysis can be regarded as a novel, cost-effective and promising electrolysis method, which causes the manufacturing of H_2 via the solar splitting of water [68]. Solar electrolysis has been able to offer an appropriate solution for important challenges of H_2 manufacturing process such as H_2 storage, transportation and provides a noteworthy opportunity to reduce deleterious and toxic gases to the atmosphere [69,70].

In current years, various investigations have been conducted to investigate the efficiency of solar electrolysis process. As an example, Ferrero and Santarelli assembled a two-dimensional water electrolyzer model for use in proton exchange membrane (PEM) fuel system in integration with photovoltaic solar cell. They resulted that the integration of PEM fuel system with photovoltaic solar cell considerably enhanced the production of H_2 [71]. Kuckshinrichs et al. developed an investigation to evaluate the economic feasibility of alkaline water electrolyzer (AWE) to produce H_2 at different European countries. Based on their study, the cost of H_2 production was around 3.64 euro per kg at Germany. Due to higher electricity cost in Austria and Spain, the cost of H_2 production was 15 and 18% higher than Germany, respectively [72]. Fig. 5 schematically demonstrates the process of H_2 production via water electrolysis.

3. Economic dimensions of H_2 production using different methods

As discussed before, disparate techniques have been currently applied to produce H_2. Techno-economic evaluation of H_2 production via disparate techniques can be an important help for scientist to predict/assess the conditions and efficiency of each industrial-based operating plant after investment. One of the promising tools to determine the capital cost of H_2 production process is the calculation of return on investment (ROI). This tool seems to have brilliant potential to determine some parameters such as the total growth of the H_2 production plant from initiation to ending and also degree of investment return at each level of plant construction [74,75]. The following equation can be derived for the calculation of the ROI [20]:

$$ROI = 100\%^{*}\left(\frac{AF}{FCI}\right) \tag{8}$$

In this equation, AF and FCI are denoted as the annual profit and fixed capital investment. In an investigation, Han et al. developed a dark fermentation pilot-scale H_2 manufacturing plant with the life span of 15 years. After calculation, the AF and FCI of H_2 manufacturing plant after tax was predicted to be 146,473.6 and 547,504 USD, respectively. In doing so, considering the Eq. 1, the ROI is calculated as 26.75% [76]. There is a direct relationship between the increment of ROI and increase of the reactor volume. Generally, the ROI value higher than 20% is profitable for scaling up the process. Thus, the ROI value for the reactors with the volume of 10–30 m^3 cannot be profitable. Whereas, the reactors with the volume of 40–50 m^3 can have the ROI value higher than 20% and therefore, are profitable for scaling up [20]. The techno-economic evaluation of capital cost is usually performed before the implementation/run of pilot plant. This action significantly prevents the risk of unnecessary economic failure [77,78]. Another important parameter, which directly affects the H_2 selling price is the feedstock price. In an article, Ramsden et al. have estimated the relationship between the cost of feedstock and H_2 manufacturing production cost via H2A Model. In their study, the H_2 production is carried out using two methods, electrolysis and SRNG. The feedstocks (electricity and NG) used in both the methods were very expensive. They perceived from their research that the feedstock cost can consist of 66 to 72% of H_2 production cost, which results in the great potential of feedstock cost to determine the price of H_2 [79]. Table 1 comprehensively presents the capital and production costs of H_2 production using different methods.

4. The role of nanotechnology in hydrogen production

Rapid enhancement in the nanomaterials fabrication for improving the efficiency of H_2 production has gained numerous attention due to strengthening the activity of the microorganisms and enhancing the physico-chemical properties of materials [84]. The use of nanoparticles has been substantially developed in recent industrial-based activities such as proteins immobilization and manufacturing of biosensors and drug delivery [85–88]. Biosensors has currently illustrated its potential to increase the electron exchange on the way to acceptors. Furthermore, nanoparticles may be able to considerably influence the microbial metabolic motion for H_2 production via improving the efficient exchange of electrons [89]. In this case, encouraging increment in H_2 production can be obtained via the incorporation of disparate types of

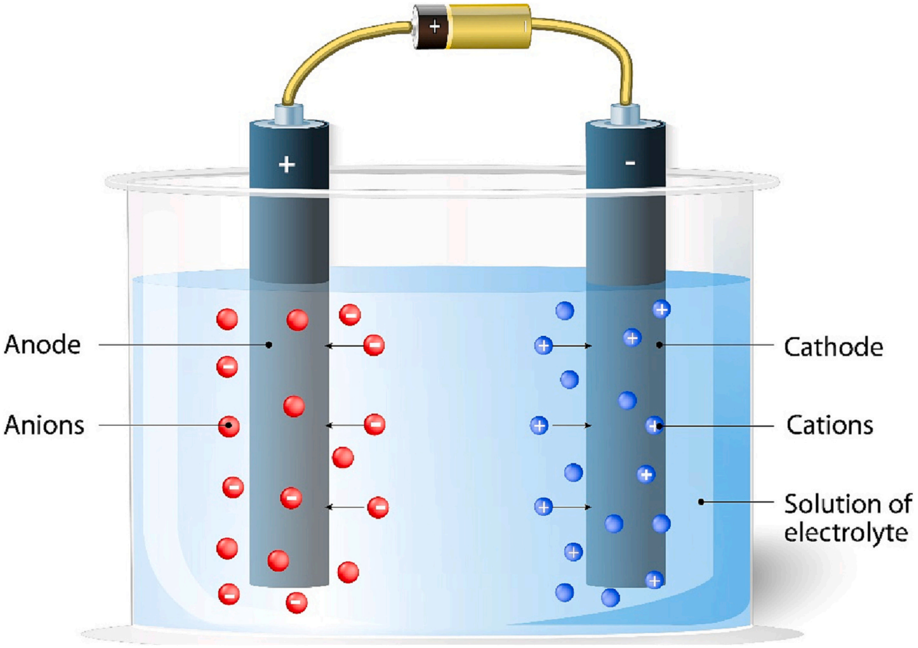

Fig. 5. Schematic demonstration of H_2 manufacturing process using water electrolysis [73].

Table 1
Comparison of capital/production cost of H_2 production via disparate techniques.

Employed technique	Energy source	H_2 production cost ($/kg)	Capital cost	Ref.
Wind electrolysis	Wind	5.89–6.03 $/kg	499.6–504.8 M$	[80]
Coal gasification	Fossil fuels	25 cent/Nm^3-H_2	507.3 M$	[81,82]
Solar thermolysis	Solar	7.98–8.40 $/kg	5.7–16 M$	[80]
Steam reforming	Fossil fuels	2.42 $/kg	3.4 M$	[83]
Biomass pyrolysis	Internally generated steam	1.25–2.20 $/kg	3.1–53.4 M$	[80]
Nuclear electrolysis	Nuclear	4.15–7.00	–	[6]

organic and inorganic nanoparticles consisting of metal and metal oxides such as gold, palladium, silica, titanium oxide and carbon nanotubes (CNTs) [90]. These nanoparticles can strengthen the biohydrogen manufacturing process by affecting their surface and quantum measure impact [91]. The synthesis process of disparate types of nanoparticles can be done applying physicochemical and organic techniques for their use in the dark fermentative biohydrogen manufacturing process. The eco-friendly synthesis of nanoparticles via organic technique, which uses the extraction process from plant leaf, has been recently of great interest as an outstanding option [92–94]. In the recent years, industrial-based employment of nanoparticles (NPs) to enhance the biological manufacturing process of H_2 has been of paramount attentions. However, true recognition about the efficiency of different organic/inorganic NPs is still in its infancy [95]. Silver NP (AgNP) may be known as a promising inorganic nanomaterial, which has currently demonstrated its potential of use in the biological production of H_2. In this case, Zho et al. experimentally investigated the effect of adding silver NPs to anaerobic batch reactors on increasing the fermentative manufacturing of H_2. They concluded from their research that the incorporation of silver NP significantly increased the efficiency of H_2 production and the maximum value of H_2 production reached to 2.48 mol/mol glucose when the concentration of silver was 20 nmol L^{-1}. It can be understood from this study that greater amount of H_2 production was due to the enhanced production of acetate and butyrate and consequently, decrement of ethanol and propionate production [92]. Gold NP (AuNP) is another efficient inorganic nanomaterial, which has been commonly used to improve the catalytic/enzymatic activities and immobilization in chemical and biological industries [84,91]. In an analytical study, Zhang and Shen studied the enhancement impact of gold NPs on fermentative H_2 manufacturing process from artificial wastewater. They perceived from their investigation that the incorporation of 5, 10 and 20 nm-gold NPs considerably enhanced the performance of H_2 production were for about 50, 40 and 20%, respectively. This result justifies the fact that gold NPs has suitable potential to increase the bioactivity of hydrogen producing microbes [91]. Silica NP (SiO_2NPs) (as an effective inorganic nanomaterial) has been recently obtained great attentions in the biological production of H_2 due to its appropriate biocompatibility for both proteins and microorganisms [96]. Later Beckers et al. studied the effect of silica as an encapsulating material for applied metallic/metallic oxide in dark fermentative process of H_2 production. Based on their investigation, the silica encapsulated Fe NPs encapsulated with silica significantly increased the H_2 production percentage by about 113% and reached to 86 mL H_2/L/h [89]. In the case of organic nanomaterials, CNTs possesses higher place. CNTs can be defined as a cylindrical structure consisting of rolled-up sheets of single-layer carbon atoms, which have shown their unique potential of use in the biosensors and microbial fuel cells owing to their indisputable role in the reduction of redox reactions and electron transfer kinetics [97]. Liu et al. evaluated the application of CNTs as novel microbial carriers to improve the performance of biological process of H_2 production. The concluded that the incorporation of 100 mg L^{-1} CNTs in a laboratory-scale up flow anaerobic sludge blanket (UASB) reactors substantially improved the H_2 production rate to 5.55 L/L/d. The results corroborated that the use of CNTs compared to activated carbon particles accelerated the initiation process and enhanced the efficiency of H_2 fermentation in UASB reactors [97]. For better explanation, Table 2 presents the effect of various organic/inorganic NPs on increasing the performance of biological H_2 production.

Table 2
Comprehensive information about the effect of different organic/inorganic nanoparticles for increasing the performance of biological H_2 production.

Employed NP	NP type (organic/ inorganic)	Optimum NP concentration	Feedstock	Biocatalyst	H_2 production increase	Ref.
Fe	Inorganic	100 mg L^{-1}	Glucose	*Enterobacter Cloacae* DH-89	100%	[98]
Au	Inorganic	0.001 mol L^{-1}	Acetate	Anaerobic sludge	N/A	[96,99]
Ag	Inorganic	20 nM L^{-1}	Glucose	Mixed culture (controlled by *Clostridium butyricum*)	67.6%	[92]
Ni	Inorganic	mg L^{-1}	Glucose	Anaerobic sludge	0.9%	[100]
SiO_2	Inorganic	40 mg L^{-1}	Gaseous mixture (97% air +3% CO_2)	*Chlamydomonas reinhardtii* CC124	45.2%	[95,101]
TiO_2	Inorganic	50 mg L^{-1}	Glucose	*C. pasteurianum* CH5	5%	[102]
Pd	Inorganic	5 mg L^{-1}	Glucose	*E. cloacae* 811,101	0.6%	[103]
CoO	Inorganic	1 mg L^{-1}	Pal oil effluent	*Bacillus anthracis*	67.4%	[104]
Hematite	Inorganic		Sucrose	Mixed culture produced by cracked cereals	32.64%	[105]
CNTs	Organic	100 mg L^{-1}	Glucose	Anaerobic sludge	N/A	[106]
Nano activated carbon	Organic	33.3 mg L^{-1}	Sucrose	Anaerobic sludge	70%	[107]

5. Environmental impacts

Over the last decades, substantial increment in the anthropogenic burning of fossil fuels has increased the concerns of international scientists/researchers about its dire consequences on the ecosystem and human health due to its direct effect on increasing the emission of toxic/ harmful greenhouse pollutants (mainly CO_2, H_2S and SO_2). Abnormal release of greenhouse gases to the atmosphere has recently increased the risk of various unfavorable events like global warming, climate change, decrement of crop yield and respiratory ailments [108–111]. With this trend of fossil fuels' consumption in the world, the annual average temperature of earth is estimated to increase 1.25, 2.2, 3.5 and 5.4 °C at the end of 2025, 2050, 2075 and 2100, respectively due to the increment of atmospheric CO_2 concentration [112]. Therefore, finding and developing novel, clean, cost-effective and safe substitution of fossil fuels is of great importance for enduring the sustainability of energy supplement. In current years, environmentally-friendly fulfillment of the GED for homemade and industrial activities is known as the most important challenge in energy sector [113]. Due to the operational/functional restrictions towards the use of fossil fuels in all anthropogenic activities, many developed and developing countries perceived this reality that H_2 energy is an appropriate solution to fulfill the GED and decrease the dependency of fossil energy sources [114–117]. H_2 has currently been introduced and received global attentions as a promising fuel pathway and energy vector due to its great potential of application as a carbon-neutral energy source in different industrial approaches [118]. Application of H_2 for energy manufacturing process significantly reduces the emission of greenhouse gases due to the production of only heat and water vapor during its production process [6,119]. Better speaking, H_2 is regarded as an important energy alternative in those regions, which are difficult to decarbonize. The presence of noteworthy advantages like great ability to improve air quality due to producing negligible amount of CO_2 (compared to internal combustion engines) has made this energy as a clean and environmentally-friendly alternative for fossil fuels [120].

6. Conclusion and future outlook

Over the last decades, the need of eco-friendly and cost-effective fuel has eventuated in the extensive application of H_2 energy all over the world. H_2 is one of the most efficient energy carriers, which its molecular form isn't abundantly existed in the nature. In doing so, the achievement of this promising energy carrier from the renewable or non-renewable energy sources is of prime importance. Recently, disparate techniques such as MSR, GSR, gasification, ATRM, photocatalytic and electrolysis of water have been implemented for the production of H_2, which their techno-economic evaluation must be done to introduce the efficient and cost-effective ones. Apart from techno-economic study of all commonly-employed H_2 production processes, another objective of this paper is to comprehensively review the important properties of H_2 production techniques. All prominent parameters, which affect the capital/production cost of H_2 production have also been under investigation in this paper. Based on this review paper, steam reforming of natural gas has been regarded as the most efficient technique of H_2 production, which has attracted the attentions various researchers and policymakers owing to its great performance in H_2 production (70 to 85%) with affordable capital (3.4 M$) and production (2.42 $/kg) cost.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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