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Biohydrogen Production from Various Renewable Resources; Current Technologies and Future Perspective

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Abstract

In the present context, the imperative need for decarbonisation is rapidly driving the push for biohydrogen as a promising biofuel for the future. The escalating pace of industrial development and urban expansion has led to significant environmental degradation, intensifying the focus on bio hydrogen. Consequently, research endeavours are directed towards its production using diverse renewable and sustainable resources. Over the past decades, numerous techniques have evolved to advance bio hydrogen production across various dimensions. To further enhance existing technologies, there is a growing emphasis on methods that are not only more efficient but also commercially and economically viable, with a particular focus on resources like solid biomass and liquid waste over other renewable sources. Thermochemical, biological and electrochemical conversions, coupled with modified pre-treatment methods employing suitable conditions and parameters, are emerging as more efficient, cost-effective means to elevate the yield of bio hydrogen generation compared to ongoing techniques. This paper specifically delves into a comparative analysis of diverse techniques developed over the years, particularly in the context of waste management systems.

Keywords: Green hydrogen • Renewable resource • Pre-treatment • Waste management • Current techniques • Bio-economy

Introduction

The renewable energy source known as bio-hydrogen, which is produced by microbiological activities, is a viable clean energy alternative. Its promise to become an endless, accessible and renewable source of clean energy has made its production an international topic of interest [1]. The synthesis of biohydrogen is dependent on a variety of parameters, including the substrate type, inorganic additives such metal particles and process operating conditions. Production basically comes from two different streams namely renewable and non-renewable resources, whereas the prominent characteristics of renewable sources over fossil fuels with the use of waste management makes a large impact on sustainability of bio life cycle [2]. Ongoing studies are focusing on a number of variety of sources like organic waste, solid waste, biomass, agricultural waste including wastewater from different streams.

Hydrogen production from different resources a comparison

From the 19th century, there have been numerous methods utilized to produce hydrogen, but the primary ones are fossil fuels, natural gas, photovoltaic electricity, waste water, solid waste and biomass wastes (Table 1). Hydrogen has several advantages for our way of life. Some of them are covered in Figure 1.

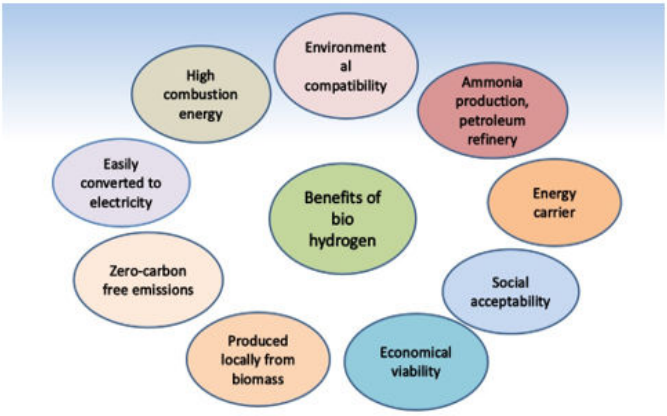

Figure 1. Benefits of Hydrogen.

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Resources	Components	Process	Advantage
Fossil fuels	Hydrocarbon molecules	Fossil fuel reforming	For Fuel Cell Electric Vehicles (FCEVs)
Natural gas: Natural gas reforming, carbon capture, utilization and storage	Methane (CH_4)	Thermal processes. reformationSteam-methane partial oxidation.	Total greenhouse gas emissions are cut in half for FCEVs.
Renewable and grid electricity	Electricity	Electrolysis	This technology is well developed and available commercially and systems that can efficiently use renewable power
Biomass	Renewable organic resource	Biomass gasification, biomass-derived liquid reforming, microbial biomass conversion	Growing biomass removes carbon dioxide from the atmosphere, the net carbon emissions of these methods can be low.
Solar	Sunlight	Solar Thermochemical Hydrogen (STCH), Photo Electrochemical (PEC), electrolysis, photo biological	Produce hydrogen with near-zero greenhouse gas emissions using water and either sunlight or nuclear energy.

Table 1. An overview of different sources from the beginning to nowadays.

There are generally three distinct sources to generate hydrogen depending on the form of feedstock, which might include solid waste, municipal sewage waste water, industrial waste and agricultural residue.

Renewable resources as a feedstock

Considering the inoculum each method hits different parameters, condition in order to acquire a better yield for hydrogen [3]. Even though having different natural resources, works are mainly focussed on the biomass, solid- liquid waste [4]. Newly emerging methods and techniques prefer these as feed stocks as these are the common environmental pollutants which makes biocycle hazardous [5,6]. Different feed stocks are picturized in Figure 2.

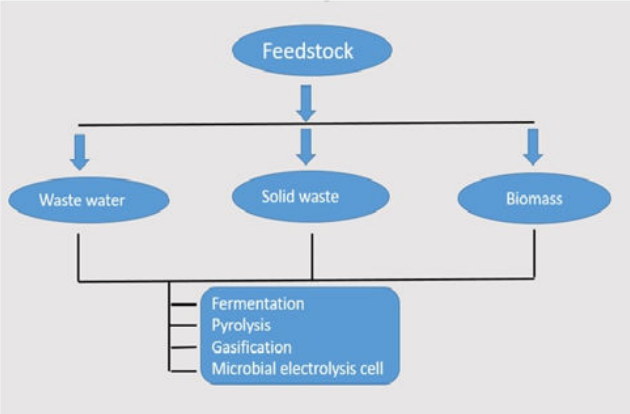

Figure 2. Different feed stock.

Materials and Methods

Pre-treatment strategies for different feedstock

Pre-treatment was very useful for improving the accessibility and reaction rate of the microbial substrate [7,8]. The pre-treatment method has the advantage of improving the rate-limiting step, which increases the yield of biohydrogen production [9]. Several pre-treatments have been introduced to improve the surface area of the substrate, such as physical, chemical, biological and combined methods [10].

Different pre-treatment methods from various renewable resources are shown in the Figure 3.

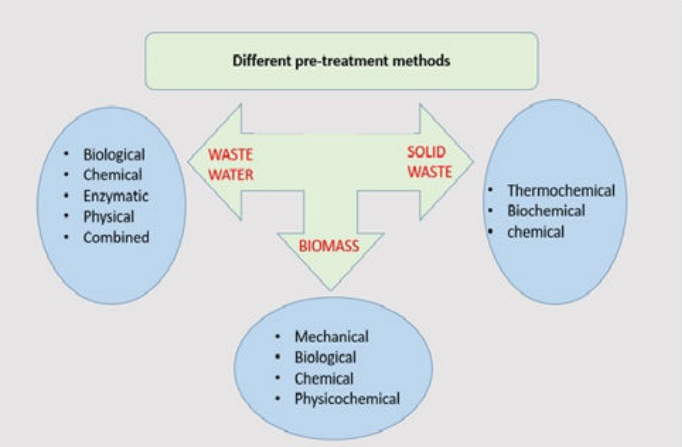

Figure 3. Different pre-treatment process.

H_2 production from wastewater

From the past decade's pollution in the waterbody has been increasing rapidly by the large population explosion which plays a major role in producing more wastes adversely affecting global climate, ecosystem, fresh resources quality and human health system.

Wastewater as a substrate

Large scale sewage production is a natural by-product of the population's growing economic growth and exploitation. They have a direct impact on energy use, global energy demand and economic growth [11]. Wastewater is a perfect resource for the creation of renewable energy because it must be legally treated before disposal. The biodegradable organic percentage of wastewater, which is linked to its innate negative net energy, is a benefit. A portion of the world's energy needs may be satisfied if wastewater could be converted into economically viable energy sources. The use of wastewater as an approach for creating hydrogen through biological operations has sparked a lot of interest because it is sustainable. The entire cost of wastewater treatment is substantially reduced by using hydrogen

produced from wastewater. A dependable source and substrate for the synthesis of bio hydrogen can be obtained by combining various wastewaters [12]. It is also understood that the hydrogen produced from sewage needs to be durable and reasonably priced. A large amount of the world's energy needs may be satisfied if wastewater could be transformed into economically viable energy sources [13].

Results and Discussion

Types of wastewaters

Waste water is generated from a wide range of sources in several fields. Industrialization and urbanization are mostly to blame for the production of waste waters. The following Table 2 provides a comparison study of the waste water sources.

Wastewater category	Type of wastewater
Food processing industry	Raw food waste
	Mushroom farm waste
	Yeast waste
	Organic wastes composed of food waste and sewage sludge
	Fruit and vegetables from unsold stocks
	Sewage sludge industrial food waste
	Slaughterhouse waste
Dairy based industry	Dairy processing
	Dairy waste permeates
	Cattle wastewater
Alcohol-based industries	Brewery wastewater
	Wine process wastewater
	Alcohol distillery
	Sugar refinery
	Molasses based wastewater
Plant/agriculture base industries	Vegetable based waste
	Paper mill
	Wheat straw hydrolysate
	Mixture of swine manure and fruit and vegetable market waste
Organic-based industries	Chemical wastewater
	Biodiesel solid residues
	Glycerine from biodiesel production
Others	Landfill leachate
	Sludge
	Filtrate of activated sludge
	Probiotic wastewater

Table 2. Different categories of waste water.

Technologies for biohydrogen production from waste water

Non-renewable fossil fuels are the main source of hydrogen generation. On the other hand, organic waste and wastewater are mostly used to produce biohydrogen. The most widely utilized technologies for producing biohydrogen from waste materials are biological fermentation, photolysis and microbial electrolysis cells, as shown in Figure 4. At the moment, wastewater is viewed as a valuable and renewable resource for resource recovery. The cost of the whole wastewater treatment process will be greatly reduced if H_2 is captured from wastewater.

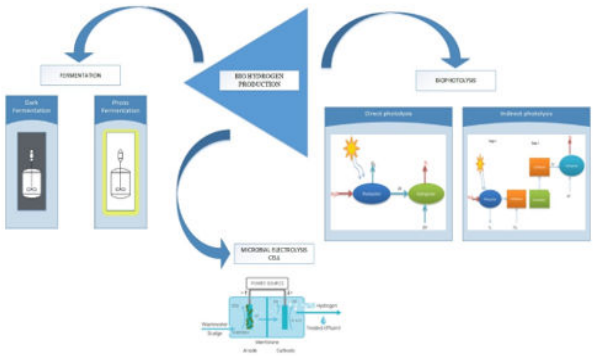

Figure 4. Different pre-treatment process.

Biological fermentation

Utilizing microorganisms capable of digesting organic waste and wastewater in anaerobic conditions, biohydrogen is created from organic waste and wastewater. Either photo fermentation, [14] which takes place when light is present or dark fermentation, which occurs when light is not present, transpires during the process.

Photo fermentation

In order to create hydrogen in the presence of light, apart from nitrogen and oxygen, photo fermentation uses photosynthetic bacteria, such as purple non-sulfur bacteria, together with an additional light source [15]. The organisms utilized in photo fermentation solely utilize photosystem-I to produce hydrogen during photosynthesis [16]. In order to split water, these organisms require extra light and they use organic acids like acetic acid to contribute their electrons to the production of hydrogen.

$$CH_3COOH+2H_2+Light \longrightarrow 4H_2+CO_2 \quad (1)$$

This equation indicates anoxygenic photosynthesis, *i.e.*, there is no production of oxygen.

Dark fermentation

It is a method that uses carbs as a source of energy or carbon. There is no need for a source of light energy for dark fermentation. In addition to carbohydrates (like glucose), it can also utilize organic substances, polymers (starch, cellulose, etc.), algal biomass and so on. It takes a number of biological events to carry out the extremely complicated process of dark fermentation.

Pyruvate and NADH are formed when glucose breaks down into its component parts by the phosphorylation of NAD.

$$C_6H_{12}O_6+2NAD^+ \longrightarrow 2CH_3COOH+2NADH+2H^+ \quad (2)$$

Two different enzymes can help convert pyruvate to acetyl CoA.

Catalysis by ferredoxin oxidoreductase

$$Pyruvate+CoA+2Fd(ox.) \longrightarrow AcetylCoA+CO_2+2Fd(red.) \quad (3)$$

Catalysis by formatelyase

$$Pyruvate+CoA \longrightarrow Acetyl\ CoA+Formate \quad (4)$$

Reoxidation of ferredoxin: The Fe-Fe hydrogenase enzyme reoxidizes ferredoxin in this step.

$$2H^++Fd(red.) \longrightarrow H_2^++Fd(ox.) \quad (5)$$

Production of hydrogen $NADH+H^+ \longrightarrow H_2+NAD^+$ (6)

Bio photolysis

It uses photoautotrophic organisms to divide water, including microalgae and cyanobacteria [17]. The energy source for these creatures is light and the carbon supply for dividing water into its component parts is carbon dioxide. As a result, anaerobic conditions are used for the synthesis of biohydrogen during bio photolysis.

$$4H_2O+Light\ energy \longrightarrow 2O_2+4H_2 \quad (7)$$

Direct photolysis

This produces hydrogen using photosynthetic algae to turn water into chemical energy using solar light as the source of light.

Biohydrogen is produced by direct photolysis in two processes:

When algae absorb sunlight, they convert water into electrons, protons and oxygen molecules.

$$2H_2O \longrightarrow 4H^++4e^-+O_2 \quad (8)$$

When the algae's photosystem-I absorbs sunlight, an electron is transferred to ferredoxin and the hydrogenase enzyme *via* the electron transport chain. Hydrogen gas is created when protons and electrons recombine.

$$4H^++4e^- \longrightarrow 2H_2 \quad (9)$$

This procedure, also referred to as one-stage photolysis, allows for the direct production of hydrogen using water, light energy and algal photosystems.

Indirect photolysis

Microorganisms that can photosynthesize, such as cyanobacteria and microalgae, are used in this procedure. Through a two-step process, indirect photolysis also transforms solar energy into chemical energy. The first step involves the photosynthetic system producing biomass. Utilizing the biomass that is high in carbs in order to create biohydrogen is the second stage.

$$6H_2O+6CO_2+Light \longrightarrow C_6H_{12}0_6+6O_2 \quad (10)$$

$$C_6H_{12}O_6+2H_2O \longrightarrow 4H_2^++2CH_3COOH+2CO_2 \quad (11)$$

Indirect photolysis needs both hydrogen and oxygen to be removed at various times in order to avoid the hydrogenase enzyme's sensitivity. Due to the fact that a reaction needs to be completed in two parts, it is also known as two-stage photolysis. *Gloebacter* sp., *Synechocystic* sp. and other cyanobacteria are utilized in the indirect photolysis process (Table 3).

Methods for the production of biohydrogen	Organisms used	Yield of hydrogen	End product
Photo fermentation	Phototrophic bacteria like purple sulphur and non-sulphur bacteria	0.16	H_2 and CO_2
Dark fermentation	Fermentative bacteria like *Clostridium*, *Citrobacter* and *Enterobacter* sp.	65-75	H_2, CO_2 and VFA
Direct photolysis	Green algae	0.07	H_2 and O_2
Indirect photolysis	Cyanobacteria	0.36	H_2 and O_2

Table 3. Showing different biological processes for the production of bio hydrogen.

Microbial electrolysis cell

If the proper technology is used, the expected clean output of the microbial process would be biohydrogen. Its production has garnered interest on a global scale due to its potential to develop into an affordable, renewable and unlimited source of clean energy.

The microbial electrolysis cell is the technology that converts waste into products with the greatest efficiency [18-20]. The MEC system uses isoelectronic microorganisms to convert biodegradable material, including organic waste, into protons and electric current. Protons and energy are produced at the anode by the bacteria's reaction with the biodegradable waste. H_2 is produced at the cathode when the protons are subsequently reduced by the electrons. Because microbial electrolysis is an endothermic process, the current production at the cathode must be induced to start by supplying a tiny voltage between the two electrodes. The applied voltage, however, is only between 0.2 and 0.8 V and can be provided by modest solar panels or low-grade microbial fuel cells. Double chamber MECs system and single chamber MECs system are the two types of microbial electrolysis cell.

Electrolysis

Electrolysis is the division of a solution into hydrogen and oxygen. An electrolyze is a device where this process takes place. The sizes of electrolyzes vary; small appliances are perfect for scattered small-scale hydrogen production, while large-scale machines are also available.

As with fuel cells, electrolysis is made up of an anode and a cathode that are separated by an electrolyte; the various types of ionic species and electrolyte materials involved determine how differently each electrolyze performs.

Photocatalysis

Using a proper photocatalyst, the process of producing photocatalytic Hydrogen (H_2) transforms solar energy into chemical energy. Comparison between various methods used for hydrogen production (Table 4).

Process	Advantages	Disadvantages
Solid gasification	Good hydrogen yield	Effective solar collector plates are required
Thermochemical gasification	Higher conversion can be achieved	Gas conditioning and tar removal is to be done
Pyrolysis	Gives carbonaceous material with oil, chemicals and minerals	Catalyst deactivation will occur
Supercritical conversion	Sewage sludge can be used easily, difficult by gasification	Selection of superficial medium
Direct bio-photolysis	H2 can be produced directly from water and sunlight	Requires high intensity of light, low photochemical efficiency and O_2 is inhibitory
Indirect bio photolysis	Blue green algae can produce hydrogen from water. It has the ability to fix N_2 from atmosphere.	Uptake hydrogenates are to be removed
Photo fermentation	A wide spectral energy can be used by photosynthetic bacteria.	O_2 is inhibitory on nitrogenase enzyme and light conversion efficiency is low. Relatively lower
Dark fermentation	It can produce H_2 without light. No oxygen limitations and can produce several metabolites as by-products. Various substances can be used in this anaerobic process. Can produce relatively high H_2 yield.	Dark fermentation suffers from low hydrogen yields, microbial competition leading to the formation of by-products and sensitivity to environmental factors, hindering its efficiency for hydrogen production.
Two stage fermentation	Can produce relatively higher H_2 yield. By products can be efficiently converted to H_2.	It increased complexity, higher operational costs and the need for precise control of intermediate products, which may limit their practicality and economic viability for certain applications.

Table 4. Comparison between various methods used for hydrogen production.

H_2 production from solid waste

Urbanization and population growth have resulted in massive garbage production and fossil fuel consumption. People are compelled to aim for a low-carbon energy system by their increased understanding of sustainable society. An increasingly popular energy source that produces no carbon is hydrogen. By producing hydrogen and getting rid of garbage at the same time, biohydrogen from organic waste has tremendous interest.

Solid waste classification

Depending on its origin, solid waste can take many various forms: Hazardous waste is categorized as industrial waste, municipal waste as household rubbish and infectious waste as biomedical or hospital waste.

Municipal solid waste

Municipal solid waste includes trash from homes, construction sites, building trash, sanitary landfills and streets. The majority of these complexes for residential and commercial waste are responsible. The consumer market has expanded quickly over the past few years, which has resulted in products being packaged in non-biodegradable materials like aluminum foil, plastic, cans and other similar items that hurt the environment incalculably.

Hazardous waste

Waste from businesses and hospitals is regarded as dangerous because poisonous compounds may be present. Household garbage can potentially be toxic in some cases. Hazardous wastes may be extremely hazardous to people, animals and plants. They may also be explosive, caustic or highly combustible. They may also react to certain substances, such as gases.

Hazardous waste might include household items like old batteries, paint tins, shoe polish, pharmaceuticals and medicine bottles. Hazardous hospital waste is waste that has been contaminated by hospital-used chemicals. These substances include mercury, which is used in thermometers and blood pressure monitors, as well as phenols and formaldehyde, which are employed as disinfectants. The primary producers of hazardous waste in the industrial sector are those engaged in the production of metal, chemicals, paper, pesticides, dyes, refining and rubber goods. It is potentially fatal to come into direct touch with toxic wastes like mercury and cyanide.

Hospital waste

When humans or animals are diagnosed, treated or immunized, hospitals produce trash, as well as during related research projects, biological manufacturing or biological testing. Wastes such sharps, unclean waste, disposables, anatomical waste, cultures, out-of-date prescription medicines, chemical wastes, etc. These take the form of bodily fluids, human excreta, bandages, disposable syringes, swabs, etc. If not handled with science and discrimination, this trash is highly contagious and poses a major risk to human health.

Important technologies

The primary methods for producing biohydrogen from garbage are:

- Microbial electrolysis cell
- Thermochemical gasification
- Biological fermentation

The most popular waste source for microbial electrolysis cells and fermentation was various forms of waste water; lignocellulose waste from agriculture was also extensively studied in fermentation. Nonetheless, wood waste and municipal solid waste were the two wastes that were gasified the most.

Biological fermentation

Biological digestion or fermentation must be used to treat solid waste. For thermophilic bacteria, it is a regulated breakdown of biodegradable materials that generates heat through biological processes. Microbes must operate on waste materials in order for biological digestion to take place in the management of solid waste. The organic materials found in garbage are broken down by microorganisms like bacteria and fungi, which are known as nature's scavengers. In other words, it is the aerobic and anaerobic processes used to break down the organic component of solid waste. During fermentation, which occurs in a closed reactor in anaerobic circumstances at temperatures ideal for mesophilic or thermophilic bacteria, biodegradable materials undergo controlled degradation.

The main byproducts of fermentation are volatile fatty acids like acetic, propionic and butyric acid as well as alcohols like ethanol and butanol. Fermentation systems are categorized as "wet" or "dry" depending on how much moisture is in the batch. "Wet" fermentation occurs when the substrate's dry matter content is less than 15%. Wet systems are often conducted in a continuous mode, which supports process stability, however "dry" fermentation can occur in both continuous and periodic modes in dry solutions. Compared to wet fermentation, dry fermentation requires a smaller reactor volume. increased concentration of dry materials, which causes waste to ferment. The maximum dry matter concentration of the substrates is 40%.

Thermochemical gasification

Thermal waste treatment is the use of heat to treat waste products. Thermal waste management techniques try to limit the amount of garbage produced, transform waste into innocuous products and use the energy stored inside waste to produce heat, steam, electricity or combustible material. Any waste treatment method that uses high temperatures to convert the waste feedstock is referred to as thermal treatment. Thermal treatment is an environmentally and financially responsible method of handling non-recyclable and non-reusable trash. Thermal treatment is the process of using heat to treat and breakdown waste materials in a variety of ways. The main thermal waste treatment technique is open burning, but this method is seen as

being harmful to the environment. Open burning does not use any pollution-controlling technology, which lets contaminants into the environment. Since it offers a less expensive option for treating solid waste, this approach is used in most nations.

Microbial electrolysis cell

A recently developed biotechnological tool known as a Microbial Electrolysis Cell (MEC) may convert carbon dioxide to produce multi-carbon biofuels like methane, acetate, etc. (a process known as electro methanogenesis)

Since many different substrates with varying degrees of biodegradability have been tested in MEC from single carbon sources thus far, the liquid component of pressed municipal solid waste (LPW), which is obtained from the pressing of the bio fraction of municipal solid waste, is a possibility for an alternative starting material.

Hydrogen production from lignocellulosic biomass

The sources of lignocellulosic biomass include agri-food by-products, agricultural waste, energy crops, marine trash and forest by-products. Dahmen, et al. estimate that each year, over 7 billion tonnes of grass and forest land are produced, which is used to produce energy. The lignocellulosic agricultural residue output is estimated to be around 4.6 billion tonnes, of which 25% is used. Due of its availability and affordability, biomass has garnered interest. More hydrogen can be produced from biomass, which increases economic capacity, increases source flexibility and lowers greenhouse gas emissions. According to Navaro, et al., biomass's preserved natural cycle allows it to be carbon neutral. Plant growth occurs through photosynthesis, which uses the CO_2 generated during the process of generating hydrogen from biomass.

Generation of H_2 from (lignocellulosic) biomass is now being pursued using a variety of technological methods, including thermochemical processes, biological conversions and possibly electrochemically aided production.

Different methods

Thermochemical productions: Aqueous phase reforming, pyrolysis and gasification are the three main thermochemical methods.

Gasification: It's an endothermic process carried out at around 1000°C in in the absence of oxygen. The synthesized gas known as syngas is created when a material consumes an oxidizing agent. It is made up of nitrogen, carbon dioxide, hydrogen and methane. Depending on the oxidizing agent used, the process can be categorized as steam gasification, oxygen gasification or air gasification. Syngas has also been shown to contain trace amounts of organic and inorganic pollutants. Light Hydrocarbons (LHC) like CH_4 and tar, a viscous liquid composed of condensable organic chemicals, are examples of the organic ingredients; inorganic molecules include NH_3, H_2S, HCl and alkali metals.

Equation (12) shows air gasification reaction of biomass.

$$\text{Biomass+Air} \rightarrow N_2+CO+H_2+CO_2+CH_4+H_2O+\text{LHC+Tar+Char} \quad (12)$$

Equation (13) shows the steam gasification of biomass.

$$\text{Biomass+steam} \rightarrow H_2+CO+CO_2+CH_4+\text{HC+Tar+Char } (\Delta HO>0 \text{ kJ/mol}) \quad (13)$$

Steam Reforming (SR) gasification: It is a purification process which reduces the Carbon-to-Hydrogen mass ratio (C/H), that improve the syngas composition. To lessen the amount of light hydrocarbons and tar that cause pipe corrosion and blockage as a result of polymerization and condensation, steam reforming has been optimised.

Supercritical Water Gasification (ScWG): In order to be more dependable for the type of biomass such as wet biomass (moisture content >35%), such as wood and carbohydrates an alternative thermochemical pathway has been developed on a smaller scale in the lab. Water needs to reach temperatures of 374°C and pressures of 221.2 bar in order to achieve supercritical fluid status. In these circumstances, both the number of hydrogen bonds and the dielectric constant of water drop. Organic compounds and gases are soluble in high-temperature supercritical water, which speeds up their conversion. The entire procedure is similar to aqueous-phase reforming and is endothermic.

Pyrolysis: Is an alternative tool for biomass thermochemical conversion next to gasification. Pyrolysis, like gasification, can be done at temperatures that are lower while removing the utilization of an oxidizing agent. To aid in the production of heat, just a tiny bit of an oxidizing agent may be applied in certain situations. Temperatures between 400°C to 800°C and pressures up to 5 bar are typical for pyrolysis.

Based on the temperature at which it operates, pyrolysis can be divided into three groups: flash pyrolysis, fast pyrolysis and traditional (or slow) pyrolysis.

Equation (14) shows a general pyrolysis reaction.

$$\text{Biomas heat} \rightarrow H_2+CO+CO_2+CH_4+H_2O+\text{bio-oil+charcoal } (\Delta HO>0 \text{ kJ / NMmol}) \quad (14)$$

A two-stage thermochemical process called pyrolysis-steam reforming has received a lot of attention recently.

Aqueous Phase Reforming (APR): This is the another thermochemical technique used to produce H_2 from biomass. APR primarily transforms oxygenated substances into hydrogen. Low temperatures are used during the aqueous phase for the dissolution and interaction of feedstock molecules with water molecules.

Biological conversion

There are three different kinds of biological conversion: dark fermentation, biologically water gas shift reaction and photo-fermentation

Each procedure is influenced by the type of enzymes that are utilized to catalyze H_2 production.

Because biological conversion takes place at a lower temperature range (30°C-60°C) and pressures (1 atm), its energy cost is considerably less in comparison to that of thermochemical processes. likewise, compared to chemical catalysts that are quickly destroyed during thermochemical transformations, the employed microorganisms can be easily renewed through replication, reducing the turnover frequency. In the field of waste management, biological processes are particularly intriguing since they allow solid leftovers, waste from agriculture, agricultural food contaminants and solid waste from municipalities to be converted. Since sewage sludge's nature is conducive to being converted through various biological processes, research into it has increased over the past 10 years.

The Biological Water Gas Shift (BWGS): The reaction's result is determined by their capacity of photoheterotrophic bacteria, can utilize carbon monoxide as their carbon supply. Through an enzymatic mechanism, these microbes can create H_2 in the dark by oxidizing CO and lowering H_2O, according to equation (15).

$$CO+H_2O \rightleftharpoons CO_2+H_2 \ (\Delta HO<0 \ kJ / mol] \quad (15)$$

Dark fermentation: Maintaining anaerobic microbes in a dark environment at temperatures ranging from 25 to 80°C or even at hyperthermophilic (>80°C) conditions, depending on the strains, is a viable biological method for creating H_2.

Photo-Fermentation (PF): Is the newest biological process used to create H_2. PF uses nitrogenizes found in purple non-sulphur bacteria to catalyze the transformation of organic compounds or biomass into hydrogen utilizing sun energy in a nitrogen-deficient medium.

Electrochemical converson possibility

For biomass, electrochemical conversion is also feasible. The distinction between biomass electrolysis and water electrolysis is the reaction occurring at the anode. The feedstock is oxidized rather than the water producing gaseous oxygen.

There exist two distinct technologies that facilitate biomass electrolysis, that are Proton Exchange Membrane Electrolysis Cell (PEMEC) and Microbial Electrolysis Cell (MEC).

Factors affecting the production of Biohydrogen from various renewable resources are shown in Figure 5.

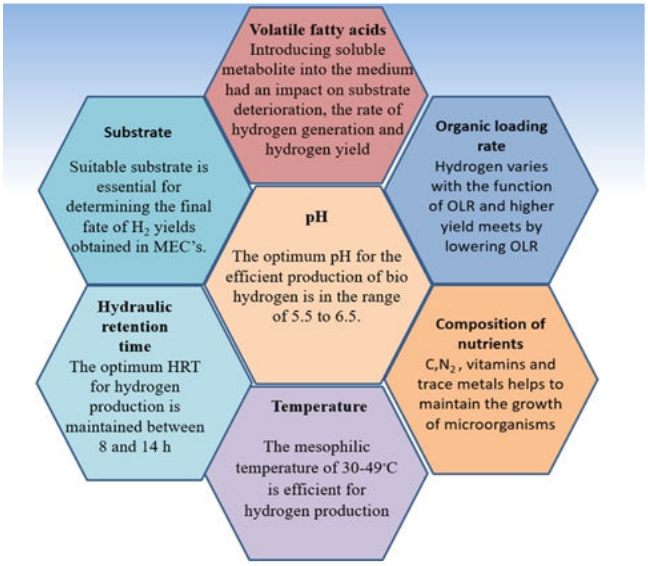

Figure 5. Factors affecting the biohydrogen production.

Comparison of main advantages drawbacks and hydrogen yields of several process options (Table 5).

Processes	Advantages	Limitations	H_2 yield (g/kg feedstock)
Thermochemical process			
Biomass gasification	Existing industrial design, forest residue and industrial waste recycling, high biomass conversion efficiency, no expensive oxygen source required in steam gasification	CO_2 emission, tar and char formation leading to catalyst deactivation, H_2 variation due to biomass complexity and composition variation, high operating temperature, need for catalysts regeneration, high reactor cost	40-190
Steam reforming	Existing industrial design, no expensive oxygen source required	CO_2 emission, high operating temperature, need for catalysts regeneration	40-130
Partial reforming	Existing industrial design, low desulfurization requirement, no catalyst requirement	CO_2 emission, high operating temperature, high cost of oxygen, adapted only for few molecules	16-140
ScWG	Suitable on biomass with high moisture content	CO_2 emission, high pressure needed, high energy consumption	20-40
APR	Suitable for feedstock in aqueous solutions	CO_2 emissions, adapted only for few molecules, need for pre-treatment.	1-40
Biomass pyrolysis	Existing industrial design, forest residue and industrial waste recycling, versatile conversion of biomass (gas, biooil, biochar), simple process	CO_2 emissions, tar and char formation, H_2 variation due to biomass complexity and composition variation, need for catalyst regeneration, high reactor cost.	25-65
Biological processes			

Dark fermentation	Organic and biological waste streams recycling, conversion of algal biomass (high growth rate), low operating temperature and pressure, various suitable carbon sources	Low H_2 yield and rate production, high by products generation, need for pre-treatment	4-44
Photo fermentation	Organic and biological waste streams recycling, nearly complete substrate conversion, low operating temperature and pressure	Low H_2 yield and rate of production, high surface area requirement, need to control the bacteria, high energy demand for enzymes, low energy solar conversion efficiency.	9-49
Electrochemical processes			
MEC	No purification required, lower electrical consumption (compared with water electrolysis), mild conditions	Expensive catalyst, low production rate, suitable for less complex molecules in solution	15-98
PEMEC	No purification required, lower electrical consumption (compared with water electrolysis), mild conditions	Expensive catalyst, low production rate, suitable for less complex molecules in solution	

Table 5. Comparison of main advantages drawbacks and hydrogen yields of several process options.

New and emerging technologies

It is evident by comparing the generation of hydrogen from various sources over the years that new technologies offer a perfect way to create a carbon-free atmosphere in an efficient manner in the future. There are numerous comparative studies available for the traditional, present and future techniques of manufacturing biohydrogen. Here, the comparative analysis is being done from the standpoint of present and upcoming methodologies based on various resources (Figure 6).

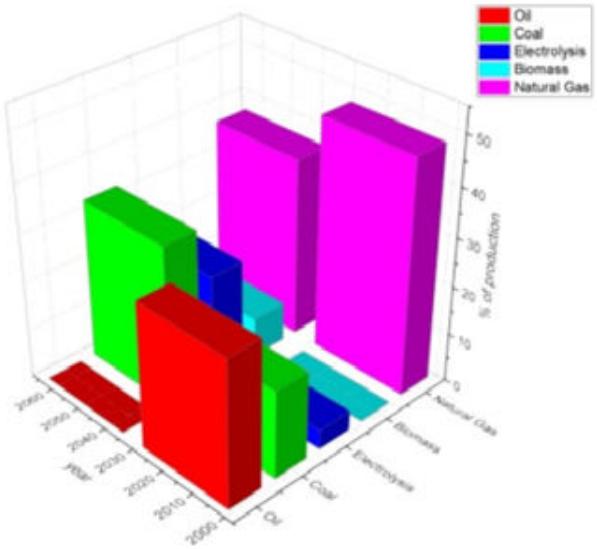

Figure 6. Comparative study of different resources from present and future sources.

In the case of wastewater

Physical, biological, chemical and sludge water treatment are the main four techniques used to treat sewage water. Following these procedures results in treated water that is safe for both human consumption and the environment. The wastewater is cleaned of all sewage materials and disinfected. Another device that can perform three functions simultaneously is microbial fuel cell technology, which uses bacteria to treat wastewater and can also generate clean electricity and store energy. The latest advances in this field include nutrient recovery and removal, energy generation and conservation, sustainability, non-traditional pollutant treatment and community involvement.

In the case of solid waste

The two biggest trends in today's society are recycling and reuse. It entails gathering garbage and turning it into fresh resources. As a result, less waste needs to be carried to landfills and less virgin resources are required. Waste-to-energy plants provide steam for electricity generation by processing solid waste as part of the circular economy, a trend for economic growth that maintains resources for longer use.

Another rising trend in trash management is the increase of cooperative efforts. It alludes to the alliances and teamwork among those involved in the waste management process. These consist of governmental agencies, neighborhood associations and private businesses.

In the case of biomass

In terms of the emergence of the hydrogen economy, biomass is anticipated to continue playing crucial roles in the large-scale production of hydrogen. by utilizing microbes' ability to help the environment. Aquatic habitats can be harmed by excess phosphorus and nitrogen, but Algal Turf Scrubbers can help to solve this issue. The algae can then be processed into biofuel.

Recent advancements in biogas upgrading methods encompass technologies such as hydrate separation, cryogenic separation, biological approaches, membrane enrichment, in-situ upgrading, multistage anaerobic digestion and high pressure anaerobic digestion.

Future scope and outlook

The development of technology for producing Hydrogen (H_2) is the subject of extensive research. Because of the massive emissions of atmospheric greenhouse gases throughout the surroundings and the depletion of petroleum oil sources, bio-H_2 is becoming an increasingly alluring source of environmentally safe and sustainable fuel alternatives. Because hydrogen gas is more akin to electricity when it comes to of energy systems, it is a better power source than fossil fuels. Bio-H_2 is regarded as a substitute renewable energy source that is generated from biomass. It is an emission-free, efficient and clean energy source.

- Offers an alternative to the grid electricity production
- Considerable attention on
- Inadequate substrate conversion effectiveness
- Build-up of acid intermediates rich in carbon
- Adaptive buffering
- Redox alteration
- A wide range of sectors need to be focussed
- Aviation
- Heavy industry
- Use of carbon capture technologies
- Development of direct electrification

Conclusion

Various processes and technologies for hydrogen production is reviewed. In the present world the details of various process are described. The production of bio hydrogen presents a viable approach to the sustainable long-term development of renewable resources. Nevertheless, there are major challenges to be addressed before switching from a fossil fuel-based economy to one that depends on bio-hydrogen energy. The two primary problems with the generation of bio hydrogen are limited substrate conversion and low productivity. The recent advancement of these technologies aids in overcoming obstacles and directs bio hydrogen generation towards widespread adoption and commercialization. The primary technical barriers to producing hydrogen on a commercial scale are the absence of fuel cells, distribution networks and hydrogen storage, in addition to pre-treatment technologies and production prices.

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Conflict of Interest Statement

The authors declare no conflicts of interest regarding this article

References

1. Kumar, Gopalakrishnan, Periyasamy Sivagurunathan, Arivalagan Pugazhendhi, and Ngoc Bao Dung Thi, et al. "A Comprehensive Overview on Light Independent Fermentative Hydrogen Production from Wastewater Feedstock and Possible Integrative Options." *Energy Conv Manag* 141 (2017): 390-402.
2. Kapdan, Ilgi Karapinar, and Fikret Kargi. "Bio-Hydrogen Production from Waste Materials." *Enzyme Microb Technol* 38 (2006): 569-582.
3. Keskin, Tugba, Haris Nalakath Abubackar, Kubra Arslan, and Nuri Azbar. "Biohydrogen Production from Solid Wastes." (2019): 321-346.
4. Zhang, Yongfang, and Jianquan Shen. "Enhancement Effect of Gold Nanoparticles on Biohydrogen Production from Artificial Wastewater." *Int J Hydrogen Energy* 32 (2007): 17-23.
5. Lertsriwong, Supattra, and Chompunuch Glinwong. "Newly-Isolated Hydrogen-Producing Bacteria and Biohydrogen Production by *Bacillus coagulans* MO11 and *Clostridium beijerinckii* CN on Molasses and Agricultural Wastewater." *Int J Hydrogen Energy* 45 (2020): 26812-26821.
6. Sun, Yong, Jun He, Gang Yang, and Guangzhi Sun, et al. "A Review of the Enhancement of Bio-Hydrogen Generation by Chemicals Addition." *Catal* 9 (2019): 353.
7. Prabakar, Desika, Varshini T. Manimudi, Swetha Sampath, and Durga Madhab Mahapatra, et al. "Advanced Biohydrogen Production Using Pretreated Industrial Waste: Outlook and Prospects." *Renew Sustain Energy Rev* 96 (2018): 306-324.
8. Mohan, S. Venkata, V. Lalit Babu, and P. N. Sarma. "Anaerobic Biohydrogen Production from Dairy Wastewater Treatment in Sequencing Batch Reactor (Ansbr): Effect of Organic Loading Rate." *Enzyme Microb Technol* 41 (2007): 506-515.
9. Mota, Vera Tainá, ADN Ferraz Júnior, Eric Trably, and Marcelo Zaiat. "Biohydrogen Production At pH Below 3.0: Is It Possible?." *Water Res* 128 (2018): 350-361.
10. Samsudeen, N, Joshua Spurgeon, Manickam Matheswaran, and Jagannadh Satyavolu. "Simultaneous Biohydrogen Production with Distillery Wastewater Treatment Using Modified Microbial Electrolysis Cell." *Int J Hydrogen Energy* 45 (2020): 18266-18274.
11. Boboescu, Iulian Zoltan, Mariana Ilie, Vasile Daniel Gherman, and Ion Mirel, Bernadett Pap, et al. "Revealing the Factors Influencing a Fermentative Biohydrogen Production Process Using Industrial Wastewater as Fermentation Substrate." *Biotechnol Biofuels* 7 (2014): 1-15.
12. Skonieczny, Monika T, and Viviane Yargeau. "Biohydrogen Production from Wastewater By Clostridium Beijerinckii: Effect of pH and Substrate Concentration." *Int J Hydrogen Energy* 34 (2009): 3288-3294.
13. Zhang, Tong, Hong Liu, and Herbert HP Fang. "Biohydrogen Production from Starch in Wastewater under Thermophilic Condition." *J Environ Manage* 69 (2003): 149-156.
14. Lin, Chiu-Yue, Chyi-How Lay, Biswarup Sen, and Chen-Yeon Chu, et al. "Fermentative Hydrogen Production from Wastewaters: A Review and Prognosis." *Int J Hydrogen Energy* 37 (2012): 15632-15642.
15. Noblecourt, Alexandre, Gwendoline Christophe, Christian Larroche, and Pierre Fontanille. "Hydrogen Production by Dark Fermentation from Pre-Fermented Depackaging Food Wastes." *Bioresour Technol* 247 (2018): 864-870.

16. Ziara, Rami MM, Daniel N. Miller, Jeyamkondan Subbiah, and Bruce I. Dvorak. "Lactate Wastewater Dark Fermentation: The Effect of Temperature and Initial pH on Biohydrogen Production and Microbial Community." *Int J Hydrogen Energy* 44 (2019): 661-673.
17. Mohan, S. Venkata, P. Chiranjeevi, K. Chandrasekhar, P. Suresh Babu, and Omprakash Sarkar. "Acidogenic Biohydrogen Production from Wastewater." (2019): 279-320.
18. García-Barcina, José Ma, José Antonio González-Oreja, and Alejandro De la Sota. "Assessing The Improvement of the Bilbao Estuary Water Quality in Response to Pollution Abatement Measures." *Water Res* 40 (2006): 951-960.
19. Dange, Pooja, Soumya Pandit, Dipak Jadhav, and Poojhaa Shanmugam, et al. "Recent Developments In Microbial Electrolysis Cell-Based Biohydrogen Production Utilizing Wastewater as a Feedstock." *Sustainability* 13 (2021): 8796.
20. Bina, Bijan, Mohammad Mehdi Amin, Hamidreza Pourzamani, and Ali Fatehizadeh, et al. "Biohydrogen Production from Alkaline Wastewater: The Stoichiometric Reactions, Modeling and Electron Equivalent." *MethodsX* 6 (2019): 1496-1505.

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