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BIOHYDROGEN PRODUCTION FROM WASTE MATERIALS: MINI-REVIEW

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Biohydrogen is a source of renewable and clean energy. Many countries are working to generate biohydrogen energy as a means of combating the present global warming trend. This review paper aims to highlight the available information on hydrogen production from municipal solid waste biomass and also highlight several factors influencing the rate of biohydrogen production and their challenges in the future. The study of hydrogen production processes was aimed at a complete understanding of modern hydrogen production technologies, both implemented in practice and under research or development. The review revealed some advantages of biological methods for producing hydrogen gas compared to chemical ones. Also, this paper identified different factors that affect the biohydrogen production process such as type of bioreactors, temperature, pH, light, nutrients. This study also brings to the surface the challenges that need attention from researchers.

Keywords: waste biomass; hydrogen production; fermentation; microbial electrolysis cells (MEC); thermal conversion; biophotolysis.

INTRODUCTION

The era, 21 century, relay completely on energy. The main source of this energy is the burning of fossil fuels. Burning of this limited source of fuels not only going to extant but it also leads to the environmental crisis. the world needs a sustainable and clean source of energy. The alternative ways of providing energy include solar, winds, tidal, biomass, etc. these alternatives are not continuous solutions it still needs fossil fuel plants to work and produce electricity.

The world's waste generation is proportional to population, and both are growing at a rapid pace. Along with energy requirements, solid waste management is also a major issue. There are many proposed ways to reduce waste, and most of them are implemented around the world. But recycled waste makes up only 5 – 10 % of the total waste produced. Disposal of waste in open dumps causes many problems, which include unpleasant odour, appearance, wastewater contamination, and water, soil and air pollution. Currently, several solutions for rational waste management have been proposed and implemented, namely: incineration, waste-to-energy processing, bio-methanation, fertilizers, and methane collection in landfills.

On the other hand, it is important to emphasize that another problem the world is facing is the lack of a sustainable and clean source of energy. Currently, the worldwide main source of energy is fossil fuels, and this dependency has been increasing exponentially. Fossil fuel resources are limited and use at this rate will deplete existing reserves and their combustion causes serious negative environmental impacts such as greenhouse gas emissions, CO_2 emissions and pollution (Jiménez-Llanos et al., 2020). The search for new and reliable energy sources continues to this day. Hydrogen production is one of them and it is called as future of energy. Hydrogen is the clean source of energy upon combustion it does not cause the greenhouse gases (GHG) emissions, acid rain, or ozone depletion but it produces water only (Kapdan & Kargi, 2006). In addition, its advantage is that the energy yield is 2.75 times higher (i.e. 122 kJ/kg) than that of hydrocarbon fuel (da Silva Veras et al., 2017). Besides this, hydrogen can be obtained from a wide range of biomass substrates and domestic waste, materials (Guo et al., 2010). On the other hand, using gasification, reforming or pyrolysis technologies of fossil fuels, about 96 % of commercial H_2 is produced (Jain, 2009). The environmental problem could be resolved up to a great extent if H_2 production technologies shifted from fossil fuels to biomass and other renewable energy sources.

Due to several attractive characteristics, hydrogen is recognized as the cleanest and most sustainable energy source. These characteristics include high energy conversion, renewable production, reliability and environmental friendliness due to zero-emissions (Chabane et al., 2017). Moreover, the use of hydrogen is not limited to just as an energy source, but is widely used as a raw material for the production of chemicals, production of fertilizers for electronic gadgets, steel processing, hydrogenation of fats and oils in the food industry, and for the removal of impurities (sulphur) in oil refineries (Salam et al., 2018), in rotor coolant, as fuel in rocket engines, as a reducing agent (Zhang et al., 2021). Due to this extremely versatile usage, hydrogen production receives global attention.

Why hydrogen production? Like other fossil fuels, hydrogen is not present in nature as a molecule. It is extracted from the raw materials (biomass, waste, water, hydrocarbons, etc.) that contain hydrogen.

This review paper aims to highlight the available information on hydrogen production from municipal solid waste biomass and also highlight several factors influencing the rate of biohydrogen production and their challenges in the future.

WASTE MATERIALS TYPES

In accordance with various sources of formation, solid waste can be broadly classified as municipal solid waste and industrial waste (solid). However, in recent years there has been a tendency to classify healthcare waste as a special group, since it includes many environmentally hazardous substances and requires special management to avoid negative environmental consequences.

Municipal solid waste

Municipal solid waste mainly includes household waste, commercial, and institutional wastes. The nature of these wastes is generally solid or semi-solid form because of moisture and time (Moeller, 2019). The fractions include in this waste are:

– Biodegradable waste to be gardening and landscaping waste (leaves, branches, grass, etc.), kitchen and table waste, and cardboard and paper waste;

– Waste of materials that can primarily be recycled, such as paper, glass, metals, some types of plastics, etc.;

– Inert waste such as construction and demolition wastes, dirt, rocks, and debris; composite waste which includes textiles, packaging (including tetra packs), waste in the form of combined plastics such as toys, interior elements and household appliances;

– Household hazardous waste, as well as toxic waste such as drugs, electronic waste, paints, chemicals, light bulbs, fluorescent lamps, aerosol cans, fertilizer and pesticide containers, batteries and shoe polish (Benali et al., 2019).

Industrial waste (solid)

Waste generated as a result of the production activities of industrial enterprises is industrial solid waste. Wastes in this class are hazardous and typically consist of used oil, waste solvents, ash, slag, toxic chemicals and slimes, as well as other wastes such as flammability, explosiveness and causticity. Waste generated in the offices of industrial enterprises is not considered industrial waste (Han & Wu, 2019).

Health care solid waste

Health care solid waste, the waste generated by hospitals that includes syringes, plastics, glass, faecal matter, gloves, cotton, pathological chemicals, medicines, human or animal tissues, bandages, cloths, sharp needles, fluids, radioactive waste. The danger of this waste is justified by the content of infectious waste, toxic chemicals and heavy metals (Diaz & Eggerth, 2008).

For biohydrogen extraction, municipal solid waste and office waste (biomass) are considered, and different processes have been found in the literature that will be explained in this paper.

RESEARCH METHODOLOGY

The current mini-review was based on papers presented in the public domain, namely: scientific publications from peer-reviewed periodicals, book and encyclopedic documents published in reliable publishing houses, and reports presented at scientific conferences. The type of paper, language of publication, geography of authors or publications were not limited. The search for eligible literature was screened using relevant keywords in English (almost all publications provide a title and abstract in English) over a period of no more than 10 years. However, if there were cross-references suitable and relevant for the current study but older than 10 years, then these sources were also taken into account.

Logically, the review was structured as follows:

Step 1: The study of hydrogen production processes is aimed at a complete understanding of modern hydrogen production technologies, both implemented in practice and under research or development.

Step 2: Parameters affecting hydrogen production was aimed at identifying technical, technological and other scientific problems that currently have not yet been solved by scientists, but are promising for the effective implementation of hydrogen production technologies and require attention from researchers.

Step 3: Summing up should present in a concentrated manner the most significant conclusions based on the results of the study.

HYDROGEN PRODUCTION PROCESSES

Figure 1 shows a generalized diagram of known processes for hydrogen production.

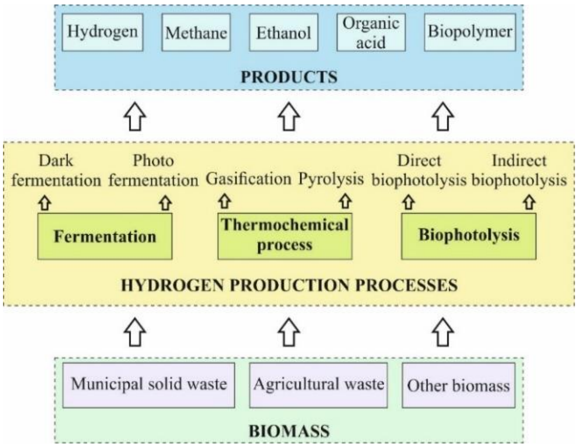

Figure 1. Hydrogen production processes

Hydrogen production from fermentation

Hydrogen production from dark fermentation

Dark fermentation is a biochemical process and is considered to be the most practical one to produce hydrogen from organic/inorganic waste (Nagarajan et al., 2017). This process takes place in the presence of anaerobic fermentative microorganisms such as Clostridium and Escherichia coli (bacteria) (Show et al., 2018). During anaerobic conditions, these bacteria are nourished themselves using organic/inorganic substrates such as glucose and sucrose and producing various microbial products that are hydrogen, fatty acids, alcohols under a dark fermentation environment.

$$C_6H_{12}O_6 + 6H_2O \rightarrow 12H_2 + 6CO_2$$

$$C_6H_{12}O_6 + 6H_2O \rightarrow 4H_2 + 2CH_3COOH + 2CO_2$$

$$C_6H_{12}O_6 + 6H_2O \rightarrow 2H_2 + CH_3CH_2\ H_2COOH + 2CO_2$$

The conversion process equations are shown (Saravanan et al., 2021), and a diagram of the fermentation process is shown in Figure 2.

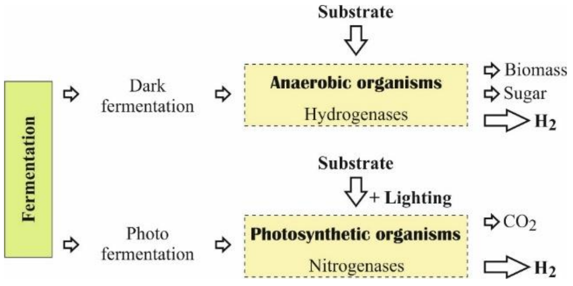

Figure 2. Mechanism of dark fermentation and photofermentation (own development based on Saravanan et al., 2021)

Hydrogen production from photofermentation

The photosynthetic bacteria (purple, no sulphur photosynthetic bacteria) are utilized in H_2 production (Basak & Das, 2007; Sagir & Alipour, 2021). In the presence of sunlight, these bacteria convert organic waste into carbon dioxide and H_2. The reaction takes place at anaerobic conditions (Saravanan et al., 2021):

$$CH_3COOH + 2H_2O + Light \rightarrow 4H_2 + 2CO_2$$

The process is shown schematically in Figure 3 (Sun et al., 2019).

The commonly used non-sulphur photosynthetic bacteria (PNS) are *Clostridium sp.*, *Rhodobacter sulfidophilus*, *Rhodopsuedomonas palustris*, *Rhodobacter sp.*, etc. (Jabbari et al., 2021).

Light intensity and light wavelength affect H_2 production. Particularly light intensity is proportional to H_2 production rate up to saturation point. The lacking of infrared light wavelengths declines the H_2 production by 39 % (Sharma et al., 2021).

Hydrogen production through microbial electrolysis cells (MEC)

At MEC, electrochemically active bacteria use organic matter (biomass) upon oxidization it generates CO_2, proton, electrons. In addition, electricity is required to drive the bio-electrochemical reactions. The bacteria released protons into the solution and ensure the transport of electrons to the anode. The electrons from the anode then transfer to the cathode through the wire and combine with protons in the solution. The H_2 is produced at the cathode (Liu et al., 2005). The simultaneous combination of bacterial electrolysis of organic matter in one reactor with the addition of voltage promotes the release of H_2 in the MEC process. If acetate is used as organic substrate in MEC, the reactions that take place at the cathode and anode respectively are as follows (Liu et al., 2010):

$$C_2H_4O_2 + 2H_2O \rightarrow 2CO_2 + 8e^- + 8H^+$$

$$8e^- + 8H^+ \rightarrow 4H_2$$

An example of the construction and operation of a two-chamber MEC is well demonstrated by the authors in (Aziz et al., 2021). The vast bacterial group is reported that are used for MEC processes such as Proteobacteria group, Firnicutes, acidobacteria, and actinobacteria group. These groups of bacteria are Proteobacteria (*e.g Shewanella oneidensis MR-1, Geobacter sulfurreducens, Pseudomonas aeruginosa, Sphingomonas xenophaga, Rhodoferax ferrireducens, etc.*), Firmicutes (*e.g., Lactococcus lactis, Clostridium butyricum, etc.*), acidobacteria (*e.g., Geothrix fermentans*), and actinobacteria (*e.g., Propionibacterium*) (Cerrillo et al., 2017).

Hydrogen production from thermal conversion of waste

Hydrogen production from biomass gasification

Biomass gasification process is a promising method for turning biomass into valuable chemicals at high temperatures (700 – 900 °C) by reacting it with various gases such as steam, air, and CO_2 (Ahmed & Gupta, 2010). Gasification produces bio-syngas, which contain significant levels of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4) (Figure 4). Wastes from the biomass gasification process include ash and tar, as well as oils and coal (Aboagye et al., 2017). The greatest influence on the gasification product composition is exerted by such process parameters as the composition of the catalyst and precursor, temperature, feedstock-to-catalyst ratio, and atmosphere. You should also consider the impact of retention duration (Kim et al., 2021).

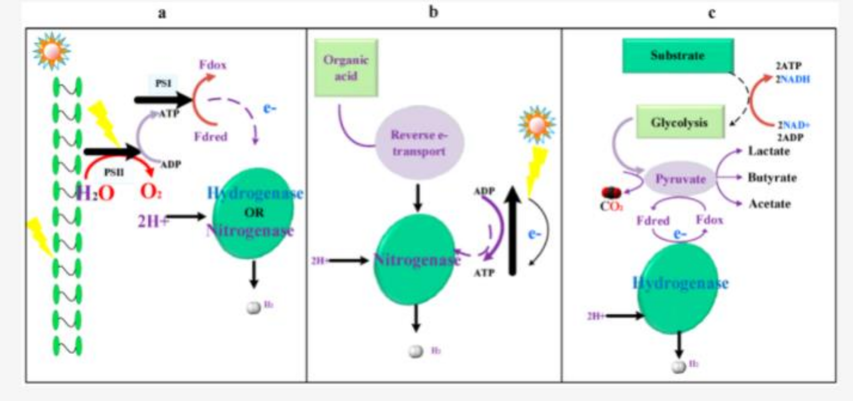

Figure 3. Biohydrogen production pathways (a) biophotolysis (b) photofermentation (c) dark fermentation, PSI means photosynthetic system 1, PSII means photosynthetic system 2, Fdox – oxidized ferredoxin and Fdred – reduced ferredoxin (Sun et al., 2019)
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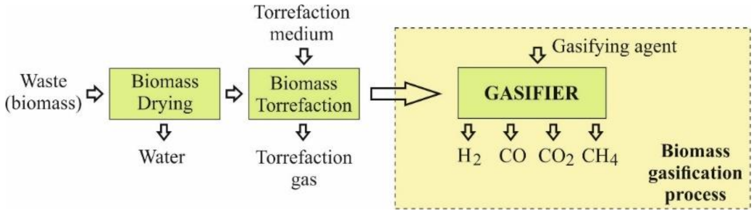

Figure 4. Gasification reagent and products (own development based on (Yong & Rasid , 2022))

Substrate drying, breakdown (pyrolysis), oxidation (gasification), and reduction (combustion) are the four steps of gasification in general (Puig-Arnavat et al., 2012). It consists primarily of partial oxidation of the precursor, extraction of energy from the substrate, and conversion of that energy into chemical bonds in the form of gaseous molecules. All possible gasification reactions can be divided into heterogeneous and homogeneous re-actions (Xiong et al., 2020).

The chemical form of writing heterogeneous reactions looks like this (Mahdisoozani et al., 2019; Gupta et al., 2018):

$$C + CO_2 \leftrightharpoons 2CO$$

$$C + H_2O \leftrightharpoons CO + H_2$$

$$C + 2H_2 \leftrightharpoons CH_4$$

$$C + 0.5\ O_2 \rightarrow CO$$

At the same time, the chemical form of writing the main homogeneous reactions looks like this (Ram & Mondal, 2019):

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

$$CO + H_2O \leftrightharpoons CO_2 + H_2$$

$$H_2 + 0.5\ O_2 \rightarrow H_2O$$

$$CO + 0.5\ O_2 \rightarrow CO_2$$

Depending on the catalysts used, the gasification agents used and other reaction parameters, some of the reactions presented above (possibly all of these reactions) can occur in the biomass gasification process (Elkhalifa et al., 2019).

During the steam gasification of FW, several possible processes normally take place. Through the water gas reaction, the carbon component in the FW initially evolves as CO. As a result of the water-gas shift and methanation reactions, it is transformed to CO_2 and CH_4, and in the majority of specified processes H_2 gas is formed. Further char gasification can eventually lead to an equilibrium reaction with optimal production of H_2 and CO (Ahmed & Gupta, 2010).

Hydrogen production from biomass pyrolysis

Pyrolysis is a process that produces liquid oils, solid chars, and the gaseous products by heating biomass at a high temperature of 400 – 650 °C in the absence of oxygen at a pressure of 0.1 – 0.5 MPa. Process variables such as pressure, temperature, and, most importantly, residence time determine the fractions of pyrolysis products. Slow pyrolysis, intermediate pyrolysis, and fast pyrolysis are the three types of pyrolysis depending on the reaction time, which defines the reaction kinetics. Hydrogen can be generated effectively by fast pyrolysis (i.e., pyrolysis with a short residence time and high heating rate) at a high temperature and a certain volatile phase residence duration.

$$C_xH_yO_z\ (\text{biomass}) + \text{heat} \rightarrow CO + H_2 + CH_4 + \text{others}$$

For a better understanding, the pyrolysis process for hydrogen production is presented in the form of a diagram by the authors of (Bakhtyari et al., 2021).

Hydrogen production from biophotolysis

Bio photolysis is an H_2 production process using the most plentiful resources on earth water and sunlight. It is a completely sustainable process because it produces water as a product and energy. It can be further classified into two types is Direct and Indirect bio photolysis (Nabgan et al., 2021).

Direct biophotolysis

In photosynthesis, the first major step is the splitting of water molecules into hydrogen and oxygen in the presence of sunlight. The green algae and cyanobacteria in the direct bio photolysis process capture sunlight and utilize this energy to dissociate water into protons (H^+), electrons (e^-), and oxygen (O_2) (Show et al., 2019). This process consists of two-step photochemical oxidation reactions given in the equations below for the Water-Splitting Process and for the Proton-Electron Recombination, respectively:

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

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

Initially, during the process of water splitting, sunlight activates photosystem II (PSII), also known as water-plastoquinone oxidoreductase, which breaks down H_2O into protons (H^+), electrons (e^-) and oxygen (O_2), and then e^- moves through photosystem I and ferredoxin (Fd). At the second stage, the proton-electron recombination occurs e- goes into Fd into Fe-Fe hydrogenase, which ultimately produces H_2 (Goswami et al., 2021). This process is clearly explained by the diagram developed by the authors in (Gangadhar et al., 2021).

Fundamentally, sulphur is a key component of the green alga *Chlamydomonas reinhardtii* (*C. reinhardtii*) photosynthetic mechanism, since it is required to repair the D1 protein, a major component of the (PSII) reaction centre (Show et al., 2018; Liu et al., 2020).

Due to sulphur limitation, there is a significant reduction in the rate of photosynthesis. In addition to this, the release of O_2 accompanying photosynthesis is reduced by a simultaneous minimal effect on the rate of cellular respiration. However, in the case of a higher rate of respiration, higher than cell photosynthesis, after approximately 24 – 30 hours under sulphur-deficient conditions, the *C. reinhardtii* culture would become anaerobic when exposed to light and subsequently start to produce H_2.

Indirect biophotolysis

To get over the problem of O_2 inhibition indirect biophotolysis, researchers have looked at the so-called "indirect biophotolysis" process, in which CO_2 is first fixed into carbohydrates and then employed in separate phases to make H_2 (Nagarajan et al., 2021).

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$

Indirect biophotolysis, where two-stage processes were applied to the transitory separation of H_2 evolution and photosynthesis, sustained H_2 production was established (Ghysels et al., 2013). Photosynthesis and biomass yield are the first stage, and in the second stage, sulphur-deficient *C. reinhardtii* subsidized with acetate can maintain H_2 segregation for several days until the deleterious consequences of sugar consumption become apparent. As a result, indirect biophotolysis processes include the separation of H_2 and O_2 evolution reactions into separate stages, which are then linked via CO_2 fixation and evolution (Rashid et al., 2013).

Indirect bio photolysis comes with its own set of issues, such as recycling photobioreactor components and lowering the chemical cost of nutrients to promote algae growth. These two things account for 80 – 85 % of a commercial hydrogen production's total cost (Bakonyi et al., 2015).

Parameters affecting hydrogen production

Types of bioreactors

The biohydrogen production process explained above are depends on different types of reactors. Each process used its own modified version of reactors in its settings.

The fermentation process uses different reactors for hydrogen production such as Continuously stirred tank reactor (CSTR), Upflow anaerobic sludge blanket (UASB) fermenter, fixed-bed reactor (FBR), and dynamic membrane bioreactor (DMBR) (Su et al., 2020). The reactors affect biohydrogen production and by just changing retention time huge difference is noted in hydrogen production and the maximum value for each bioreactor using glucose as a substrate is shown in the Table 1.

On the basis of oxidizing agents, there are three different biogas reactors (Table 2). The production of H_2 affects a lot on the oxidizing agent. The least production of H_2 is in air gasification as compared to oxygen and steam oxidizing agent. This is because the air gasifier required dried raw materials.

Table 1. The reactor's types and its affect biohydrogen production

Reactor	HRT, hour	HPR, L/day	HY, mol H_2/Glucose	Reference
CSTR	6	11.6	2.14	Palomo-Briones et al., 2018
UASB	2	10.78	1.4	Su et al., 2020
FBR	6	4.73	0.89	Karapinar et al., 2020
DMBR	3	60.5	2.39	Park et al., 2019

HRT – Hydraulic retention time, HY – Hydrogen yield, HPR – Hydrogen production rate

Table 2. Gasification reactor types on the basis of types of bed used (Lepage et al., 2021)

Parameter name	Gasification		
	air	oxygen	steam
Products	N_2, CO, H_2, CO_2, LHC (CH_4, C_2H_4), H_2O	CO, H_2, LHC (CH_4, C_2H_4), CO_2	H_2, CO, CO_2, LHC (CH_4, C_2H_4)
Average share of H_2	0.15	0.40	0.40
Reactors	Fixed bed gasifier	Entrained-flow reactor	Fixed bed gasifier

The bed considerations affect the process of gasification and products with variations in parameters. Illustrations of the classification of gasifiers based on Bed are clearly presented by the authors of (Sharma et al., 2021).

Unlike other types of gasifiers, these do not require lengthy biomass preparation and feeding, gasification control with variable parameters, or the use of oxygen as a gasification agent. Gasifiers are categorized as updraft or downdraft depending on how they are fed. Biomass and a gasifying agent are the two primary inputs for gasification.

Temperature

The main determinant of biohydrogen production is temperature. The temperature in a mesophilic environment is thought to be affordable and simple to control on a big scale. In a mesophile environment, biohydrogen production requires less energy. Thermophilic temperature, on the other hand, results in higher biohydrogen productivity (Kargi et al., 2012). The increase in temperature to a thermophilic state has a negative impact on the efficiency of the process. For example, Lee et al., 2006 looked into the effect of temperature on biohydrogen production in a granulated biosolids bed reactor and found that increasing the temperature slowed the growth of biomass or granular formation due to enzyme denaturation and metabolic paralysis, which reduced biohydrogen production. The high energy consumption and expense is another important disadvantage of thermophilic temperature.

pH

pH has an impact on microbial activity. This is because bacteria are sensitive to pH changes in their environment, and even minor changes in pH can trigger changes in microbial metabolism. Because microorganisms are most active in near-neutral environments (Pawar et al., 2022).

Light

In the biohydrogen manufacturing process, light is the most critical factor. The reduction of carbon in starch or glycogen is aided by light in photosynthesis. Photo-decomposition requires the use of light as well. Light needs increase over time in microalgae cultivation. Microalgae require the right amount of light to thrive. Excessive light might cause photo-inhibition or energy waste during the early stages of growth. As a result, the light should be added gradually. The cells do not experience photo-inhibition at the beginning or light deprivation at the end of the progressive light supplementation.

Intensity of light

At the beginning of the anaerobic condition, a lot of light is required. Anaerobic conditions are reached sooner in a higher light than in low light. The optical light intensity of C. reinhardtii was reported to be 30 – 40 micromol/m^2/s by Laurinavichene et al., 2004. For maximum hydrogen generation, R. sphaeroides O.U needs a light intensity of 270 W/m^2. As the light intensity increased from 88 to 405 W/m^2, the light conversion efficiency of R. sphaeroides O.U fell from 1.11 to 0.25 %. However, the reduced light conversion efficiency did not affect the hydrogen yield (Laurinavichene et al., 2004). The ideal light intensity for R. plastics has been determined to be 680 micromol/m^2/s (Kim et al., 2006). Microalgal investigations, unfortunately, use a variety of units of light intensity. As a result, comparing the light intensity required by various microbes is difficult.

Wavelength of light

The wavelength of light has an impact on hydrogen yield. Microalgae cultivation and hydrogen generation require a wavelength of 20 – 30 nm. The wavelengths of different illumination sources are different. Light Emitting Diodes (LEDs) have shorter wavelengths (20 – 30 nm) than monochromatic lights. LEDs produce more hydrogen than other light sources (Uyar et al., 2007).

Challenges and improvements

H_2 is considered to be an alternative energy carrier (Show et al., 2012). As a fuel concept, H_2 is mainly used in fuel cells for energy production because of its high thermal efficiency. On the other hand, the commercialization of H_2 as a fuel is still a barrier because of high production cost, reliability, and ductility (Rahman et al., 2016).

The mass production of H_2 from waste can reduce the dependence on fossil feedstock. But it also possesses some challenges. The major challenge is the availability of biogenic waste, although waste production is abundant, for the biological process of H_2 production the collection, segregation, pre-treatment, transportation, and storage on a large scale are still the major challenge (Okolie et al., 2021).

The process of H_2 production is energy-intensive, costly. The utilization of H_2 as fuel on a mass scale faces the challenge of purification, storage, and transportation (Sarangi & Nanda, 2020). Firstly, in the purification process, the H_2 separation from a complex biological gas mixture is a difficult task as CO_2, water vapor, hydrogen sulphide, etc. possess a greater risk to gain the required purification efficiency (Bakonyi et al., 2012; Lin et al., 2007). Secondly, the H_2 storage and used as a fuel faces the difficulty of energy efficiency, durability refuelling time, and cost. Thirdly, H_2 produce in centralized or decentralized facilities for their transportation to filling station is a challenge (Olabi et al., 2021). In centralized facility lower H_2 generation cost but higher transportation cost, while in decentralized facility low transportation cost and higher H_2 generation cost (Liu et al., 2020). H_2 transportation depends on geographical location like it may be transported through pipelines, tanks via roads or ships (Rawoof et al., 2021). H_2 generated through biological process needs proper infrastructure for H_2 generation and transportation.

The mentioned bioprocessing route poses different challenges some of which are listed in Table 3.

Table 3. Some challenges in H_2 production

Route of bioprocessing	Problems as per sources: Buitrón et al., 2017; Muylaert et al., 2017; Kumar et al., 2021; Sharma et al., 2021
Direct biophotolysis	PSII activity causes O_2 to be produced. Customized photobioreactors are in high demand (design and cost) Production of H_2 is low (H_2 synthesis processes)
Indirect biophotolysis	Hydrogenases lead to low H_2 production. An external light source is in high demand. Light conversion efficiency is really low.
Dark fermentation	Inefficiency in substrate transformation Production of H_2 is low. Limitations due to thermodynamics As a product, a combination of H_2 and CO_2 gases must be separated.
Photo-fermentation	The requirement for an external light source Day and night cycles with sunlight as the light source limit the process. Low light transformation efficiency results in poor H_2 generation.
Gasification	High operational cost. limitations with the technologies. Long residence time in hours. Product gas cleaning requirement. High grinding requirement for feedstock. High oxygen consumption.
Pyrolysis	Production and purification of pyrolysis gas are costly. Carrier gas is required to maintain the inert environment, increasing operating costs. Low energy efficiency.

CONCLUSION

As a renewable, environmentally abundant source of energy and as an important feedstock for some industrial applications, hydrogen has significant value. In this regard, there is an increase in demand for hydrogen product. The most well-known methods for producing hydrogen gas are autothermal processes and steam reforming of hydrocarbons. Unfortunately, it should be noted that due to high energy consumption, these methods are unprofitable. Biological methods for producing hydrogen gas have some advantages over chemical ones. Bio-photolysis of water by algae, as well as dark and photo-fermentation of organic materials, microbial electrolysis cells by electrochemical active bacteria, thermochemical conversion of waste material through gasification and pyrolysis, and finally bio photolysis, are the main biological processes used to produce hydrogen gas. Every system has their own problem to deal with such as fermentation has a raw material cost, production is low. The Photolysis major problem showed in the literature on low H_2 production due to hydrogenases and high demand of external light source and low light conversion efficiency. In addition, Gasification's major hurdle on mass scale productions is high capital and maintenance cost. On the other hand pyrolysis, production, and purification of pyrolysis gas are costly, carrier gas is required to maintain the inert environment, low energy efficiency. The operation parameter discussed were also a key that affects the H_2 production. To advance the state of the art in bio-hydrogen production on a commercial scale, extensive research and development are required.

Declaration of conflicting interest

The authors declare no competing interests.

Contributions

Conceptualization: W.A.; Data curation: W.A.; Formal Analysis: W.A.; Investigation: W.A.; Methodology: W.A.; Supervision: F.S.; Visualization: F.S.; Writing – original draft: W.A.; Writing – review & editing: W.A., F.S.

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