International Journal of Environmental Science and Technology (2020) 17:559–576
https://doi.org/10.1007/s13762-019-02577-z

REVIEW

Biohydrogen production from waste materials: benefits and challenges

M. Kamaraj[1] · **K. K. Ramachandran**[2] · **J. Aravind**[2]

Received: 1 July 2019 / Revised: 28 September 2019 / Accepted: 29 October 2019 / Published online: 6 November 2019

Abstract

Escalating global energy demand has opened up a wide avenue for alternative energy research. One such alternative energy is biohydrogen (H_2) which is now projected as clean energy, since harnessed by biological means with high energy content; it finds the application on a broader scale. Recently, the employment of sustainable energy origins for generating biohydrogen has gained traction worldwide. Biohydrogen sourced from organic resources mainly of waste origins promises to provide sustainable energy in comparison with its other counterparts. The current work spotlights the various waste materials sourced for the generation of biohydrogen, bio-processing approaches, various microbes involved, conditions, factors, various relative advantages, and challenges. Diversities in biohydrogen processes such as utilizing different waste materials and biomass as raw material, probed akin to their chattels in the environment, bioreactor operative factors (temperature, pH, and partial pressure) are summarized. In this article, we have pursued to explicate the major hurdles confronted while procuring biohydrogen as a profit-making proposition by creating an appraisal of its improved role, also taking into account the diverse mechanism and procedures, while assessing its future perspectives.

Keywords H_2 yield · Fermentation · Organic waste · Factors · Biomass · Energy

Introduction

In the current scenario, civilization mainly depends on energy. Nation's developments are sustained by their energy surplus, because it is the key indicator for its advancement economically. The energy dependence and reserve of country gains traction in the context of large investments needed to attain the growing energy demand. At present, only conventional fossil fuels are targeted as a major source to meet the global energy requirements. The scenario of growing deficiency of fossil resources and the incremental aggregation of greenhouse gases (GHGs) in the environment is no longer unavoidable as the situation already has surpassed the "critically high" threshold, and over dependence of fossil fuel has made it as unsustainable (Singh and Rathore 2017). The emission of GHGs into the atmospheric environment owing to the increasing usage of fossil fuels attributes varied environmental threats like global warming, adverse and unpredictable climate shifts, biodiversity disruptions, ebbing of glaciers, and climb in sea level (Nikolaidis and Poullikkas 2017). Hence, the need for alternative green energy has become paramount. Sustainable energy origins are considered as an attractive surrogate to traditional fossil fuels and are predicted to be the central energy provider in the future that could augment the energy supply freedom with emission control and deliver a sustained profit for the farmers. Scientists are inspired by the attributes like renewable, sustainable, efficient, alternative green, and economically viable energy sources in order to overcome the burden sustained due to energy dependency, environmental protection, and viability focus on futuristic energy sources like biohydrogen (Gupta et al. 2013). Walsh et al. (2017) claim that amidst assorted available energy fount, hydrogen, biofuels, natural gas, and synthetic gas arise as leading, significant, ecologically prudent energy origins in the foreseeable time to come.

Hydrogen (H_2) finds broad spectrum in various purposes—being locomotive fuel and for power generation as

---

Editorial responsibility: M. Abbaspour.

✉ J. Aravind
dr.j.aravind@gmail.com

[1] Department of Biotechnology, College of Biological and Chemical Engineering, Addis Ababa Science and Technology University, 16417 Addis Ababa, Ethiopia

[2] Dr. G.R.D Institutions, Coimbatore 641014, Tamilnadu, India

it is a green energy bearer with huge energy load. Currently, fossil resources are supplying most of the hydrogen demand; these processes require high energy during hydrogen production (Argun et al. 2017). Hydrogen, as a fuel outshines other hydrocarbon fuels, because its energy efficiency high, it is recyclable, and it is considered as a green energy (Perera and Nirmalakhandan 2010). It has a high latent to be utilized in fuel cells for electricity generation due to its promising amount of energy content (140 kJ g^{-1}) (Oey et al. 2016). Various admirable attributes of hydrogen in contrast to conventional fuels eclipse its constraint in the generation mechanics (Staffell et al. 2019). Currently, hydrogen generation is limited as it is not easily available in nature and the production technologies are usually very expensive and unsustainable (Manoharan et al. 2019). Hydrogen as a fuel is either employed for direct combustion or in a fuel cell, by forming the by-product of water. Although a range of processes is applicable for H_2 production, all of them can be classified based on raw materials used into two leading divisions, specifically traditional and renewable technologies (Nikolaidis and Poullikkas 2017). In this current review, a pursuit has been contrived to appraise the current tendencies, the available technologies, processes and procedures in biohydrogen generation sourced from assorted organic waste ingredients, with a compilation of the merits and demerits of biohydrogen generation also briefly discussed.

Hydrogen production from biomass

All natural organic materials that are renewable, in extension to agronomical by-products, plant and trees, timber and wood debris, terrestrial and aquatic plants, grasses, animal residues (e.g., slurry or manure), or urban wastes (Kannah et al. 2019), etc., have been considered as biomass. Harnessing energy from biomass is an effective alternative due to zero net CO_2 effects than alternative to conventional feedstocks (Das et al. 2008). This is because when biomass is converted into hydrogen energy it counterbalances the measure of CO_2 consumed amid flourishing cycle while biomass is formed. Biomass-derived fuels contributing CO_2 is considerably marginal than the CO_2 derived from fossil-origin fuels, which is accepted as characteristic biomass carbon balance.

A chief obstacle in discharge of biohydrogen as a suitable energy source is its dearth in its feature and the necessity for economically viable conversion methods (Chandrasekhar et al. 2015). Nevertheless, feedstock issues, such as cost, logistics and supply, etc., are main weakening issues which influence the overall economics of the biomass to hydrogen production techniques (Staffell et al. 2019). Biomass, which is suitable for biohydrogen production, is broadly divided into two categories, namely (1) bioenergy crops and (2) agricultural/wood-processing wastes. Based on their origin, those can be further classified as plant- or animal-oriented biomass. In extension, amalgamated or pure microbial cultures were tapped for bioconversion of plant biomass to hydrogen, and the usual batch operational modes employed extensively have been recently substituted by continuous hydrogen production experiments (Salem et al. 2018). Figure 1 summarizes the different hydrogen production methods.

Hydrogen production from waste

Common anthropogenic activities are rejecting into the environment a wide range of materials in day to day practices. In the context existing energy scheme, global scientists progressively alter their focus from curbing pollution to resourcing waste for value added production like tapping green energy. Biological modes to treat wastewater are finding more traction, due to its versatile attributes like technical superiority, simplicity, economy, and ecofriendly. Waste materials used in the hydrogen production are segmented as agricultural waste, municipal waste, industrial waste, and other hazardous wastes. These are further compartmentalized as organic waste materials originating as or from food processing, crop residues, industry, animal manures, agricultural residue, domestic, and community wastes (Korres et al. 2013; Arizzi et al. 2016). Manipulating wastes as a probable source for H_2 generation has incited due interest for its sustainable nature and for opening new opportunity for the comprehensive use of everlasting renewable energy sources (Venkata Mohan et al. 2013; Zhang et al. 2007a, b; Venkata Mohan and Pandey 2013; Saidi et al. 2018).

Municipal solid wastes

Due to global population rise, municipal solid wastes (MSW) generated annually are rising and this escalation is disastrous. Cheap and abundant material availability is the key advantage of MSW over other wastes. In addition, it contains both macro- and micronutrients such as carbohydrates, lipids, proteins, minerals, and vitamins. These nutrient-rich MSW can be contemplated as a suitable source for hydrogen fermentation. Usually, direct fermentation of MSW proves to be less fruitful as various interfering agents hinder the process by reacting with the organic fractions (Lay et al. 1999). Since two-third of the organic component of MSW are bioprocessed for biohydrogen generation, many literature endorse MSW as the most potential source (Korres and Norsworthy 2017; Panigrahi and Dubey 2019).

Food waste

In general, food refuse can be designated as a credible source for generating energy, achieved through anaerobic

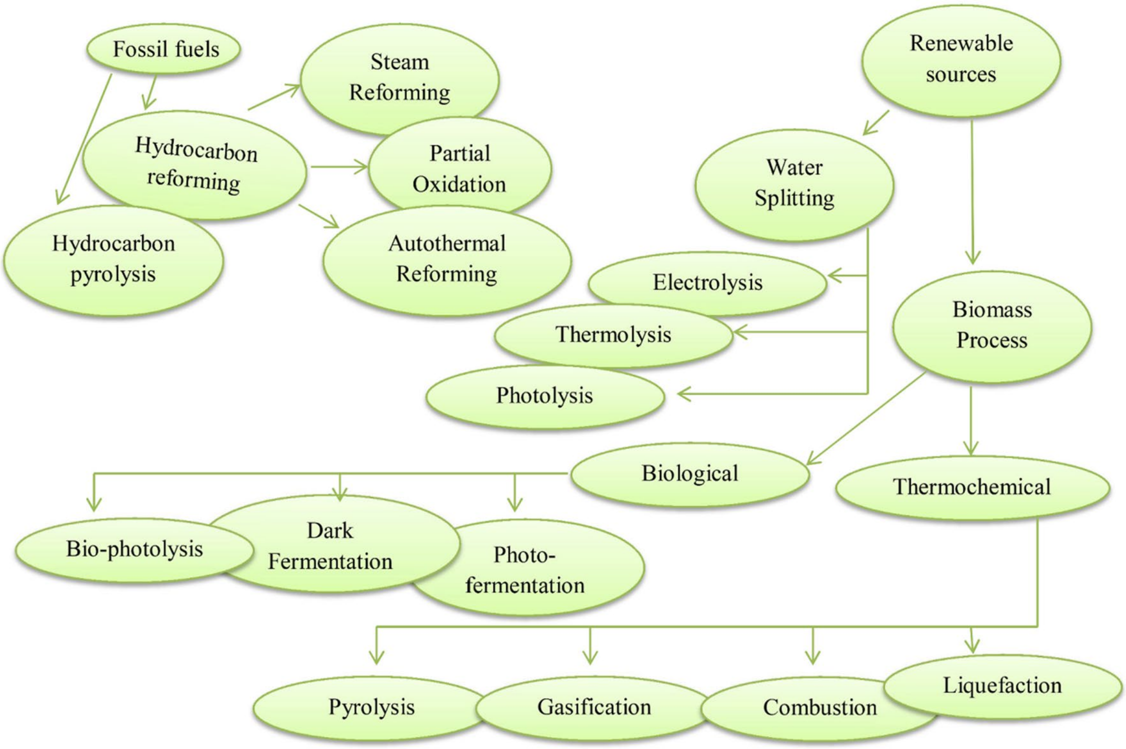


Fig. 1 Selective hydrogen production methods

degradation and also for its other beneficial attributes (Hwang et al. 2011). The physiochemical features of foodstuff rejects are key factors in developing a suitable process for biohydrogen production. Important parameters such as pre-operation processing of foodstuff rejects, ambient temperature, optimal pH and critical partial pressure determine the rate of biohydrogen generated and output (Dinesh et al. 2018). To harvest higher quantities of biohydrogen, after considering above factors, other aspects such as moisture load, volatile solid available, nutrients composition, and biodegradability are in addition paramount (Zhang et al. 2007). Biohydrogen generated from food rejects has been explored in large by various composite cultures from sources like anaerobic sludge, compost from various modes (Table 1).

Agricultural residual waste

Agriculture can easily be adjudged as the most profitable and viable process in the globe, and every year it leaves behind major volume of refuse, amounting to several billion tons, and this waste has carbohydrates in both simple and polymeric forms literally untapped (Ren et al. 2009). A significant portion of fruits and vegetables is lost or wasted during harvest, transport, and in the market, according to a Food and Agriculture Organization of the United Nations (FAO) analysis (FAO 2011, 2013). Several million tons of unmarketable vegetables could therefore be potentially sourced as biomass for dark fermentation, due to their carbohydrate content. Cellulose and hemicelluloses are the best degradable portions of the lignocellulosic matrix that can be used to produce biohydrogen by anaerobic flora (Menon and Rao 2012; Chatellard et al. 2017). Biohydrogen production from different agricultural residues by batch process is given in Table 2.

Animal generated waste

Disproportionate load of manure (and its slurry) produced from animal feeding operations were considered to be advisable resource for bioenergy production, but also found to be an incessant water polluter. Farmers can convert manure and slurry obtained at the culmination of the livestock management into biohydrogen by fermentation, which gives some financial along with positive environmental benefits (Sorathiya et al. 2014), but it has not been completely successful due to their chemical characteristics (Korres et al. 2013). Studies claim, in order to boost hydrogen yield, the animal waste can be helpful as a co-substrate due to its degradable nature and being a rich nutrient. The inclusion of an ambient pH along with microelements is needed for productive hydrogen

Table 1 Biohydrogen production from organic wastes

Substrate	Microorganism	Hydrogen yield	Fermentation mode	References
Distillery effluent	Coculture of *C. freundii* 01, *E. aerogens* E10, and *R. palustric* P2	2.7 mol H_2 mol^{-1} hexose	Batch	Vatsala et al. (2008)
Cattle wastewater	Mixed culture	12.4 mmol H_2 g^{-1} COD	Batch	Tang et al. (2008)
Microcrystalline cellulose	*C. acetobutylicum* X9 þ and *Ethanoligenens harbinense* B49	1.8 L H_2 L^{-1}POME	Batch	Wang et al. (2008a, b)
Condensed molasses fermentation soluble	Coculture of *Clostirium sporosphaeroides* F52, *and C. pasteurianum* F40	1.8 mol H_2 mol^{-1} hexose	Batch	Hsiao et al. (2009)
Probiotic wastewater	Mixed culture	1.8 mol H_2 mol^{-1} hexose	Batch	Sivaramakrishna et al. (2014)
Olive pulp water	Mixed culture	2.8 mol H_2 mol^{-1} hexose	Continuous	Koutrouli et al. (2009)
Cheese whey wastewater	Mixed culture	22.0 mmol H_2 g^{-1} COD	Continuous	Azbar et al. (2009)
Brewery wastewater	Mixed culture	6.1 mmol H_2 g^{-1} COD	Batch	Shi et al. (2010)
Vinasse wastewater	Mixed culture	24.9 mmol H_2 g^{-1} COD	Batch	Fernandes et al. (2010)
Domestic sewage		6.0 mmol H_2 g^{-1} COD		
Glycerin wastewater		6.0 mmol H_2 g^{-1} COD		
Coffee drink manufacturing wastewater	Mixed culture	0.20 mol H_2 mol^{-1} hexose	Continuous	Jung et al. (2010)
Purified terephthalic acid	Mixed culture	19.3 mmol H_2 g^{-1} COD	Continuous	Zhu et al. (2010)
Cellulosic wastes	Anaerobic sewage sludge	3.6 mmol H_2 g^{-1} cellulose	Batch	Lay et al. (2012)
Rice spent wash	Mixed culture	464^{i}	Batch	Roy et al. (2012)
Wheat straw	*C. saccharolyticus*	3.6–4 mol H_2 mol^{-1}	Batch	Willquist et al. (2011)
organic waste of composting plant	–	36 ml g V S^{-1}	Batch	Boni et al. (2013)
Rice straw	*Clostridium*, *Prevotella*, *Paludibacter*, *Ensifer*, *and Petrimonas*	1.19 mol H_2 mol $glucose^{-1}$	Continuous	El-Bery et al. (2013)
De-sugared molasses	*Thermoanaerobacterium thermosaccharolyticum* and *Thermoanaerobacterium aciditolerans*	132 ml H_2 G VS^{-1}	Continuous	Kongjan et al. (2013)
cornstalk	Anaerobic sludge	12 L kg^{-1} TS^{-1}	Batch	Liu et al. (2014)
Potato, pumpkin waste, other agro-industrial wastes	Anaerobic sludge	46 ml H_2 VS^{-1}	Batch	Ghimire et al. (2015)
Food waste	*A. awamori* and *A. oryzae*	85.6 ml g^{-1} food waste	Continuous	Han et al. (2015)
organic solid waste	Anaerobic granular sludge	0.6 mmol H_2/gVS	Continuous	Castillo-Hernandez et al. (2015)
POME	Anaerobic sludge	16 ml H_2 gVS^{-1}	Batch	Suksong et al. (2015)
Whey waste	*Clostridium* sp.	6.35 ± 0.2 mol-H_2 mol-$lactose^{-1}$	Batch	Patel et al. (2016)
Compost waste	–	1.2 ± 0.01 ml g^{-1} VS	Batch	Arizzi et al. (2016)
Organic solid waste and distillery effluent	Anaerobic sludge	5.29 mol H_2 kg COD^{-1}	Batch	Mishra et al. (2017)
Cheese whey and wheat straw hydrolysate	Anaerobic sludge	4554.5 H_2 L^{-1}	Batch	Lopez-Hidalgo et al. (2018)
Cottage cheese whey and fruit vegetable waste	*Clostridium butyricum*, *Streptococcus henryi*	118.12 ± 1.05 mmol L^{-1}	Continuous	Basak et al. (2018)
Vinasse	*Oxalobacteraceae*, *Lactobacillaceae*	1.59 ± 0.21 mol H_2 mol $glucose^{-1}$	Batch	Sydney et al. (2018)
Sugarcane bagasse	*T. thermosaccharolyticum* MJ1	6.2 L-$H_2$$L^{-1}$	Continuous	Hu et al. (2018)
POME	Digested sludge	2.45 mol-H_2 mol-$sugar^{-1}$	Continues	Mahmod et al. (2019)

Table 1 (continued)

Substrate	Microorganism	Hydrogen yield	Fermentation mode	References
Dairy industry wastewater	Biomass from fermenter	2.56 ± 0.62 mol H_2 mol carbohydrate^{-1}	Continuous	da Silva et al. (2019)
POME	POME sludge	0.416 L H_2 g^{-1} COD-removal	Batch	Mishra et al. (2019)
Beverage wastewater	Activated sludge	72 ± 31 mL L-d^{-1}	Continuous	Lay et al. (2019)
Complex food waste	Seed sludge	149 ml H_2 g^{-1} Volatile solid added	Batch	Gadhe et al. (2014)
Food waste	*Aspergillus awamori* and *Aspergillus oryzae*	85.6 ml H_2 g^{-1} substrate	Continuous	Han et al. (2015)
Waste bread	*Aspergillus awamori* and *Aspergillus oryzae*	7.4 L Ld^{-1}	Continuous	Han et al. (2016)
Food waste	Anaerobic digestion sludge	174.6 ml H_2 g^{-1} Volatile solid	Continuous	Cheng et al. (2016)
Food waste	*C. butyricum*	362 ml H_2 g^{-1} Volatile solid	Batch	Kanchanasuta et al. (2017)
Food industry waste	*Ruminococcaceae*, *Enterobacteriaceae*	101.75 ± 3.717 L H_2 kg^{-1}	Continuous	Alexandropoulou et al. (2018)
Food waste	Mixed cultures	71.34 ml H_2 g^{-1} Volatile solid	Batch	Rafieenia et al. (2019)
Waste wheat	Anaerobic mixed culture	654.7 L H_2 kg^{-1}	Continuous	Gorgec and Karapinar (2019)

POME palm oil mill effluent

Table 2 Biohydrogen production from different agricultural residues by batch process

Substrate	Type of inoculum/pretreatment	Biohydrogen yield	References
Wheat straw	Seed sludge from H_2-producing CSTR	5.69 ml H_2 g Volatile solid^{-1}	Nasirian et al. (2011)
Wheat straw	Mesophilic anerobically digested sludge	10.52 ml H_2 g Volatile solid^{-1}	Quéméneur et al. (2012)
Wheat stalks	Anaerobic digested activated sludge	23 ml H_2 g Volatile solid^{-1}	Chu et al. (2011)
	Anaerobic digested dairy manure	37 ml H_2 g Volatile solid^{-1}	
Rice straw	Anaerobic sludge	24.8 ml H_2 g Total dissolved solid^{-1}	Chen et al. (2012)
Soybean straw	Cracked cereal acclimated in continuous stirred tank reactor (CSTR)	5.46 ml H_2 g Volatile solid^{-1}	Han et al. (2012)
Sunflower stalks	Anaerobic digested sludge	2.3 ml H_2 g Volatile solid^{-1}	Monlau et al. (2012)
Mixed vegetable and potatoes	Indigenous microflora	19 ml H_2 g Total dissolved solid^{-1}	Marone et al. (2014)
Beet pulp	Seed sludge	90.1 ml H_2 g COD^{-1}	Ozkan et al. (2011)
Fruit and vegetable waste	*T. maritima*	3.46 mol mol^{-1}	Saidi et al. (2018)
Fallen leaves	Sewage sludge	37.8 mL g^{-1} VS^{-1}	Yang et al. (2019)
Agro-industrial waste	*Consortium from Eisenia foetida* lixiviated earthworm	232.72 ml H_2L^{-1}	Oceguera-Contreras et al. (2019)
Wheat straw hydrolysate	*Escherichia coli WDHL*	269.2 cm^3 H_2 g total reducing sugars^{-1}	Lopez-Hidalgo et al. (2017)
Sugar cane bagasse	Purple non-sulfur bacteria	1.96 mol H_2 mol sugar^{-1}	Mirza et al. (2019)
Rice straw	Anaerobically digested sludge	129 ml gCOD^{-1}	Kannah et al. (2019)
Mixtures of agro-industrial wastes	Anaerobic granular sludge	4554.5 ml H_2 L^{-1}	Lopez-Hidalgo et al. (2018)
Various agricultural biomass residues	Anaerobic sludge	762.3 ml H_2 L^{-1}	Ren et al. (2019)
Mixed agriculture residue	Anaerobic sludge	472.75 ml H_2 L^{-1}	Li et al. (2018)
Corn stalk pith	Photosynthetic consortium	2.6 ± 0.3 mol H_2 mol sugar consumed^{-1}	Jiang et al. (2016)

harvest. From a manufacture-economic perspective, the possible utilization of cheaper materials as auxiliary nutrients for biological conversion processes should be evaluated (Ahmad et al. 2019). Co-digestion procedure is generally used for increasing biogas production, since it provides balanced amounts of nutrients and a required buffering capacity, which also results in reducing the cost of nutritional supplements and pH control (Esposito et al. 2012). Recent studies demonstrated the increased hydrogen production with the addition of cattle manure as a carbohydrate-rich substrate. Manure is reported as a vital source for isolation of different efficient hydrogen-producing bacteria (Chatellard et al. 2017) and also reported as good biomass source for competent hydrogen fermentation (Ahmad et al. 2019). Wu et al. (2010) observed a high H_2 yield reaching 1.5 mol H_2 mol^{-1} glucose at mesophilic temperature (37 °C). Table 3 includes reported results for hydrogen status with their main parameters dealing with co-fermentation of different animal wastes.

Wastewater

The conversion of organic wastes into hydrogen is an impressive strategy in both energy recovery and pollution control aspects. Due to deficiencies related to inhibition and microbial shift, very limited research has probed real wastewater as potential source for hydrogen generation (Hafez et al. 2009). Literature studies using wastewaters as substrate for hydrogen production via dark fermentation, including wastewaters of domestic use and from industries such as paper mills, starch and food processing, rice winery, palm oil mill, glycerol-based, chemical, cattle, dairy process, rice industry, winery, noodle industry, sugar processing, sugar beet and molasses manufacturing, etc., have been recorded

Table 3 Biohydrogen production from different manures and process conditions

Substrate/substrate pretreatment	Process conditions (g L^{-1}, °C, pH)	Type of process	Hydrogen production	References
Cow slurry/No	13.4, 37, 8.2	Batch	0.7 ml H_2 gVS^{-1}	Yokoyama et al. (2007)
Buffalo manure/No	8, 37, 6.7	Batch	10.4 ml H_2 gVS^{-1}	Concetti et al. (2013)
Buffalo slurry/sterilization	2.06%VS, 37, 6.5	Batch	6.57 ml H_2 gVS^{-1}	Marone et al. (2015)
Dairy manure/acid pretreatment	50.0, 36,7 .0	Batch	18.1 ml H_2 gVS^{-1}	Xing et al. (2010)
Buffalo manure/sterilization	8, 37, 6.7	Batch	37.7 ml H_2 gVS^{-1}	Concetti et al. (2013)
Cow manure slurry/minced to 1-mm mesh size and passed through a sieve	6%VS, 60, 5.2	Semi- CSTR	10.25 ml H_2 gVS^{-1}	Wang et al. (2013)
Swine manure/shredding and filtration 1-mm mesh size	3.32%VS, 70, 6.7	Batch	3.65 ml H_2 gVS^{-1}	Kotsopoulos et al. (2009)
Buffalo manure/LPCW*/crude glycerol/(20/70/10)/sterilization	8, 37, 6.7	Batch	170 ml H_2 gVS^{-1}	Concetti et al. (2013)
Buffalo slurry/cheese whey/(33VS/67VS)/sterilization	2.06%VS, 37, 6.5	Batch	117 ml H_2 gVS^{-1}	Marone et al. (2015)
Liquid swine manure/beet molasses/(0.75/10 g/L sugar)/sieved and boiled for 30 min	12, 37, 5.4	Sequencing batch	1.57 mol H_2 mol^{-1} sugar	Wu et al. (2013)
Liquid cow manure/cheese whey/olive mill wastewater (5/40/55)/No	63.52, 37, 6	Batch	23.8 (0.64 mol H_2 mol^{-1} glucose)	Dareioti et al. (2014)
Liquid cow manure/cheese whey/olive mill wastewater/(5/40/55)/No	84.69, 37, 6	Continuous	0.54 mol H_2 mol^{-1} glucose	Dareioti and Kornaros (2014)
Cattle manure/slaughterhouse risk material/(90 (wt dry matter)/10 (wt dry matter)) Heated at 90 °C for 3 h	40, 55, 7.1	Batch	33 ml H_2 gVS^{-1}	Gilroyed et al. (2010)
Cow manure/milk waste/(30/70)/Sieved and heat-treated/–	40, 55, 6.5	Batch	59.5 ml H_2 gVS^{-1}	Lateef et al. (2012)
Swine manure/fruit-vegetable waste/[35(w/w)/65(w/w)]s Sieved/shredded in a blender	20, 55, 5.45	Semi-continuous	126 ml H_2 gVS^{-1}	Tenca et al. (2011)
Microalgae/Swine manure/ultrasonication with enzyme pretreatment	5, 35, 7	Batch	116 ml H_2 gVS^{-1}	Kumar et al. (2018)
Buffalo manure/cheese whey/	4, 55, 4.8–5	Continuous	215.4 ml H_2 gVS^{-1}	Ghimire et al. (2017)

(Balachandar et al. 2013). In relation to this, blending different wastewaters can serve as a compelling source and as a substrate in harnessing biohydrogen. For example, blending carbon-rich wastewater with nitrogen surplus wastewater may lead to improved hydrogen yield (Huang et al. 2010). Apart from this, a combination of wastewater and solid organic wastes, sewage sludge developed from the wastewater system can also be considered as an approach for biohydrogen production.

Ample accessibility and being cheap in comparison with other wastes are very strong attributes of wastewater or effluents. In spite of these attractive qualities, it has not intrigued researchers to serve as a source for inoculum considerations (Kotay and Das 2008). Hence, like MSW these also require pre-operation processing to make eligible this wastewater/sludge suitable as a substrate for dark hydrogen fermentation, despite the rich methanogenic bacteria population present in it. Properly processed sewage sludge/wastewater usage can considerably bring down the expenditure of hydrogen generation and may also prove valuable and effective handling of these types of waste.

Fermentative hydrogen production

Usually, pretreatment of biomass can be assorted as physical and mechanical means, chemical route and via biological aide. Pretreatments could be employed in the context of biomass structure as a single process or a combination of various processes (Tu and Hallett 2019; Panigrahi and Dubey 2019). The impacts of pretreatment choice on the biomass structure are illustrated in Fig. 2. Reduction of size or disintegrating the biomass structure with the aid of a physical force is grouped as physical pretreatment. Usually, high-temperatures are accompanied with severe acidic or alkaline chemical pretreatment. Biological pretreatments, can be adept at using microorganism at ambient operating environment, but are less effective in their transformation rates and yield of monomers from the composite carbohydrates (Wang and Yin 2018). The intention of seeking pretreatment steps is usually to assist microbial approach the usable sugars within the biomass (Argun et al. 2017).

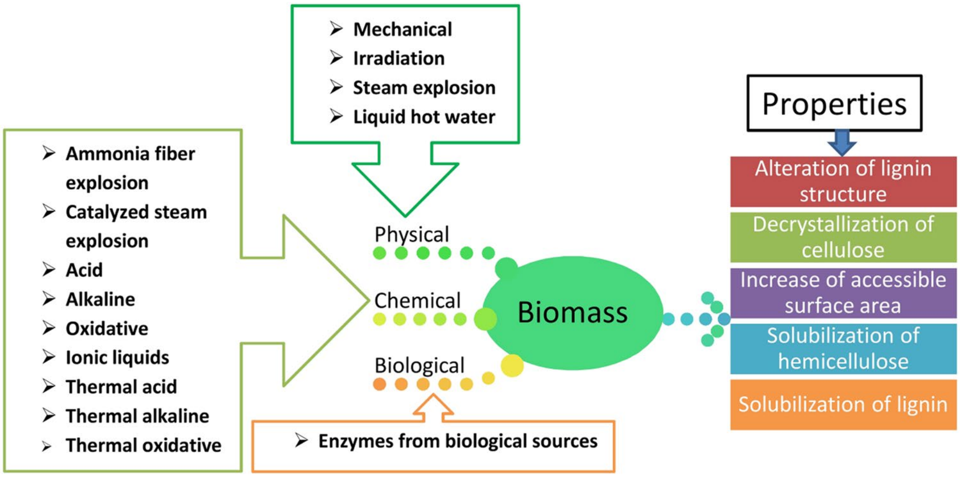
Hydrogen production by anaerobic bacteria mediated fermentation is renowned as more preferred biological routes, because of the ability of these organisms to produce the valuable biohydrogen energy from biomass and organic wastes (Sen et al. 2016). Different fermentation such as direct biophotolysis, dark, combined sequential dark-photo, and photofermentation were explored for H_2 production (Wang and Yin 2018).

In the direct biophotolysis process by involving solar energy, water molecules are split into hydrogen ions and oxygen. Hydrogenase enzymes convert these hydrogen ions into H_2. Divergent cyanobacteria and variety of micro- and macro-algal species were explored for producing H_2 (Hallenbeck and Benemann 2002; Das and Veziroglu 2008; Holladay et al. 2009). Elimination of O_2 poses a challenge in this process, as it acts as an inhibitor of hydrogenase enzyme action and therefore hinders H_2 production (Miandad et al. 2017).

The indirect biophotolysis system comprises two stages. On the first stage, O_2 is discharged with CO_2 fixation and in the second stage H_2 is generated (Momirlan and Veziroglu 2005). The mechanism of direct biophotolysis can be borne in a single reactor achieving O_2 and H_2 generation in an fluctuating cycle or in separate reactors like open ponds and photo-bioreactors (Miandad et al. 2017).

In microbial electrolysis electrical current is spawned by the bio-electrochemical system that produces H_2 in action by reduction of protons are called bioelectro-hydrogenesis. The microbial electrolysis cell (MEC) constitutes four excerpts, which are, electronic separator, cathodic chambers, anodic chambers, and external electrical power source (Hamelers

Fig. 2 Different pretreatment methods on biomass structure



et al. 2010; Miller et al. 2019). Domestic and industrial wastewater and agro-industrial residues containing cellulosic and starch biopolymers are utilized by this process to produce H_2. Key factors such as microbial physiology and physico-chemical transport processes influence the performance of the MEC. Still the greatest threat is to retain the electrical potential in harmony at both the bioanode and biocathode chambers (Liu et al. 2005; Miandad et al. 2017).

The gram-positive bacteria were found encouraging, because under dark conditions they were reported for higher hydrogen yield and rate of biohydrogen accumulated. The endospore formation and fast growing nature of the microbes make them as a better choice for industrial applications. The volume of hydrogen harnessed from glucose by bacterial culture is influenced by metabolic pathway and finished products (Krupp and Widmann 2009: Gadhae et al. 2015).

In photofermentation operation, the existence of light is essential for the photoheterotrophic bacteria, to modify organic acids (e.g., lactic, butyric and acetic) to CO_2 and hydrogen covered by anaerobic conditions. Hence, at the time of acidogenic reaction, the formed organic acids are transformed into H_2 and CO_2 by these photoheterotrophic anaerobic microorganisms. The photofermenter system has to be constructed with appropriate dissemination of light in order to limit shading, higher surface area to volume ratio are mandatory in any externally lit up photo-bioreactor at commercial scale (Zhang et al. 2019). Overall chemical reactions involved in the above-mentioned biological H_2 generation compiled in Fig. 3.

Sequential dark and photofermentation was a productive approach in biological hydrogen gas production. Dark fermentation and photofermentation can be connected because the refuse from dark fermentation was enough to source the organic acids needed for photofermentation which give rise to higher biohydrogen yield than the individual fermentation process (Zhang et al. 2019). Assorted microorganisms are competent in H_2 generation from any accessible renewable substrate covered under moderate environmental setting, which make such biological approach quite attractive compared with conventional process (Cai et al. 2019).

Factors affecting biohydrogen process

Biological hydrogen production mechanisms are not only environmentally friendly, but also inexhaustible (Benemann 1997; Greenbaum et al. 1983). In extension, the hydrogen output and the rate of hydrogen generation from various processes are shifting due to the outcome of some factors which are intricate in those procedures.

pH: pH is known to be one of the leading environmental components bearing upon the metabolic pathways and the hydrogen yield. During glycolysis, many facultative anaerobes are capable of generating hydrogen by the disruption of glucose to pyruvate. Metabolites generated midst breakdown of pyruvate, in turn, influence the hydrogen yield (Preethi et al. 2019). Metabolites that encompass supplementary hydrogen atoms such as ethanol and other alcohols are not exhibited in their corresponding acids. All the enzymes are dynamic only in a particular range of pH and have utmost activity at the optimal pH (Lay et al. 1997; Dinesh et al. 2018).

Carbon source: Carbon sources impact nitrogenase activity, which disturb hydrogen synthesis by cyanobacteria. Variations in electron donation competencies of nitrogenase are

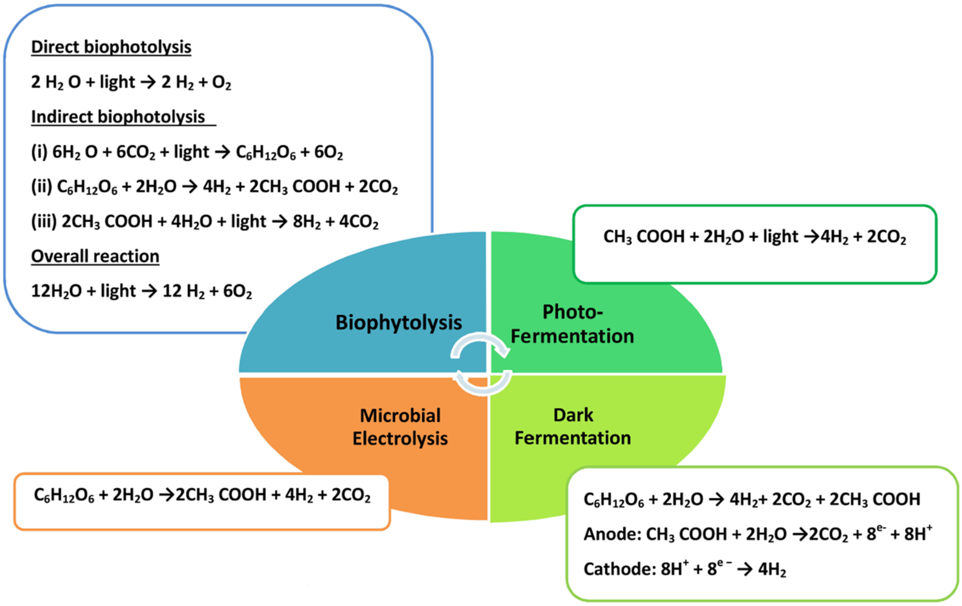


Fig. 3 Reactions involved in the biological H 2 production methods

influenced by varying concentrations of carbon sources and thus alter hydrogen production. During photosynthesis/fermentation, the starting load of glucose in the substrate was found to facilitate hydrogen yield (Gorgec and Karapinar 2019). The hydrogen generation decreased with increasing glucose concentration beyond 10 g L^{-1} (Nagarajan et al. 2019; Dinesh et al. 2018; Preethi et al. 2019).

Temperature: Variable temperature range has been reported for harnessing biohydrogen: mesophilic (25–40 °C), thermophilic (40–65 °C), extreme thermophilic (65–80 °C), or hyperthermophilic (> 80 °C) (Preethi et al. 2019). Scrutiny of literature exposed that most of the investigations conducted at the level of laboratory scale have been carried out using mesophiles (Li and Fang 2007). The findings highlight the role of temperature as a significant effector on hydrogen generation (Balachandar et al. 2013).

Hydrogen Partial Pressure: Hydrogen partial pressure is one of the sensitive parameters to be considered while exploring generation of biohydrogen. Partial pressure of hydrogen in the system would get boosted if H_2 get aggregated in the headspace. As per Le Chatlier's principle, if hydrogen gets accumulated, the onward reaction will be largely hindered. Thus, the greater partial pressure of hydrogen in the reactor, the larger its impact on generation of hydrogen negatively (Balachandar et al. 2013). Investigations have also highlighted that the partial pressure of hydrogen is a crucial aspect of extended hydrogen production (Nagarajan et al. 2019).

Volatile Fatty Acid (VFA): In fermentative hydrogen creation, metabolic end by-products were established for the decline in hydrogen yield. Ethanol, acetic acid, butyric acid, and propionic acid were found to form as the dominant end metabolites (Preethi et al. 2019). However, the medium ionic strength heightened with the increment of soluble end metabolites, which increased cellular lysis toward the stationary phase. To regulate the limiting issue of VFAs on hydrogen production, introducing soluble metabolites into the medium had an impact on substrate deterioration, the rate of hydrogen generation, and hydrogen yield (Kumar et al. 2019; Sydney et al. 2018; Balachandar et al. 2013).

Nutrients: It is crucial to add nitrogen, phosphate, and other inorganic trace minerals, amidst fermentation operation, to enable escalated hydrogen yield, while employing carbohydrate as a nutrient source for hydrogen production (Balachandar et al. 2013). Nitrogen is an indispensable component of amino acid synthesis and is required for optimal growth of the microorganism. In this scenario, Yokoi et al. (2002) demonstrated the suitable alternation of corn-steep liquor for sourcing nitrogen. Appreciable load of phosphate is also enticing for enhancing comprehensive achievement of the process and also for optimal hydrogen generation (Lin and Lay 2004). Additionally, the C/N ratio is crucial in sustaining the dark fermentation and influencing the hydrogen fecundity and specific hydrogen production rate (Lin and Lay 2004). However, maximal VFA retention in the system is not advisable as it switch the cellular reductants away from hydrogen transformation (Balachandar et al. 2013).

Gaseous Environment: Oxygen-susceptible attribute of the enzymes impact on hydrogen generation, it is mandatory to sustain an anaerobic atmosphere in the system. Impact of gaseous environment on biohydrogen production has been reported by various authors (Nagarajan et al. 2019). Generation of hydrogen was found to be naturally influenced by the existence of varying concentrations of inert or anoxic gases like argon, CO_2, and CH_4. Yoon et al. (2002) described increased hydrogen production by *Anabaena variabilis* when CO_2 was introduced repeatedly during the growth cycle, exposure to CO_2 heightened the levels of reductants impacting enhanced hydrogen yield during the process.

Metal Ions: Augmenting specific metal ions in the media are also paramount to any fermentation process. These metal ions are intricate in the cellular transport mechanisms and also participate as enzyme cofactors. According to Nicolet et al. (2010), hydrogenase is a key enzyme for hydrogen generation and it contains a bimetallic Fe–Fe center surrounded by FeS protein clusters. Many researchers consider the effect of supplementation of iron for biohydrogen production, during the glycolysis process. Voet et al. 1999 showed the role of magnesium ion as a critical cofactor for enzymes like hexokinase, phosphofructokinase, and phosphoglycerate kinase. In yet another article, Lin and Lay (2004) proved the effect of assorted trace elements such as Mg, Na, Zn, Fe, K, I, Co, Mn, Ni, Cu, Mo, and Ca for hydrogen production.

Hydraulic Retention Time (HRT): The volume and flow rate in a reactor, average duration of fermentation are important factors while considering, design, energy requirements, cost in operation, etc. Optimal HRT is paramount in the hydrogen generation process. Sourcing microbial cultures screened for their ability to sustain the mechanical disruptions created by the continuous volumetric flow is considered the paramount parameter in the overall process (Silva-Illanes et al. 2017; Lu et al. (2019).

Economics of biohydrogen production

Many countries have initiated the promotion of numerous ways for biohydrogen generation as it showed promise as a surrogate source of energy. Despite ample findings through scientific investigations and notable momentum in improving the rate of biohydrogen production, there are only limited research information available on its economics while considering avenues for commercialization (Kaushik and Sharma 2017). Construction and development of the bioreactor and the assembly systems designated for harnessing biohydrogen prove to be final during cost analysis and estimation. Most optimal production methods were assessed by important considerations involving various facets, including energy requirements, hydrogen yield, and production dexterity. Some of the cost estimates highlighted by different biohydrogen scientific explorers reported a provisional cost scenario which would aid in appraising the prospects of biohydrogen role as fuel for varied utilities in the future (Sekoai and Daramola 2015). Cost, performance, distribution and storage issues, environmental profits, national plan and policy and rules and legislation are the predominant concerns in introducing hydrogen as a fuel and also impact consumer choices, by stimulating the use of hydrogen (Nagarajan et al. 2019).

Challenges of waste-to-hydrogen energy production

In the recent years, focus on biological mode of hydrogen generation has extensively heightened among researchers. Yet, only a few studies have addressed the economic feasibility of commercial biohydrogen production. Dutta et al. (2005) showcased the lower price of photobiologically harnessed hydrogen much lower ($25 m^{-3}) in contrast to photovoltaic processed ($170 m^{-3}). Lee (2016) forecasted the cost of energy for biohydrogen will be sustained at 2.5$/Kg and would compete well with fossil fuel cost in the future. Experimental studies favored dark fermentation as a cheap method; contrary to that photofermentation was a more efficient method, but it was found to be relatively pricier. The function of the indirect photolysis approach of hydrogen production was anticipated to be around 1220$ per GJ/year, while the capital cost was predicted to be 2.4$/gigajoule/year (Menetrez 2012; Ghosh et al. 2017).

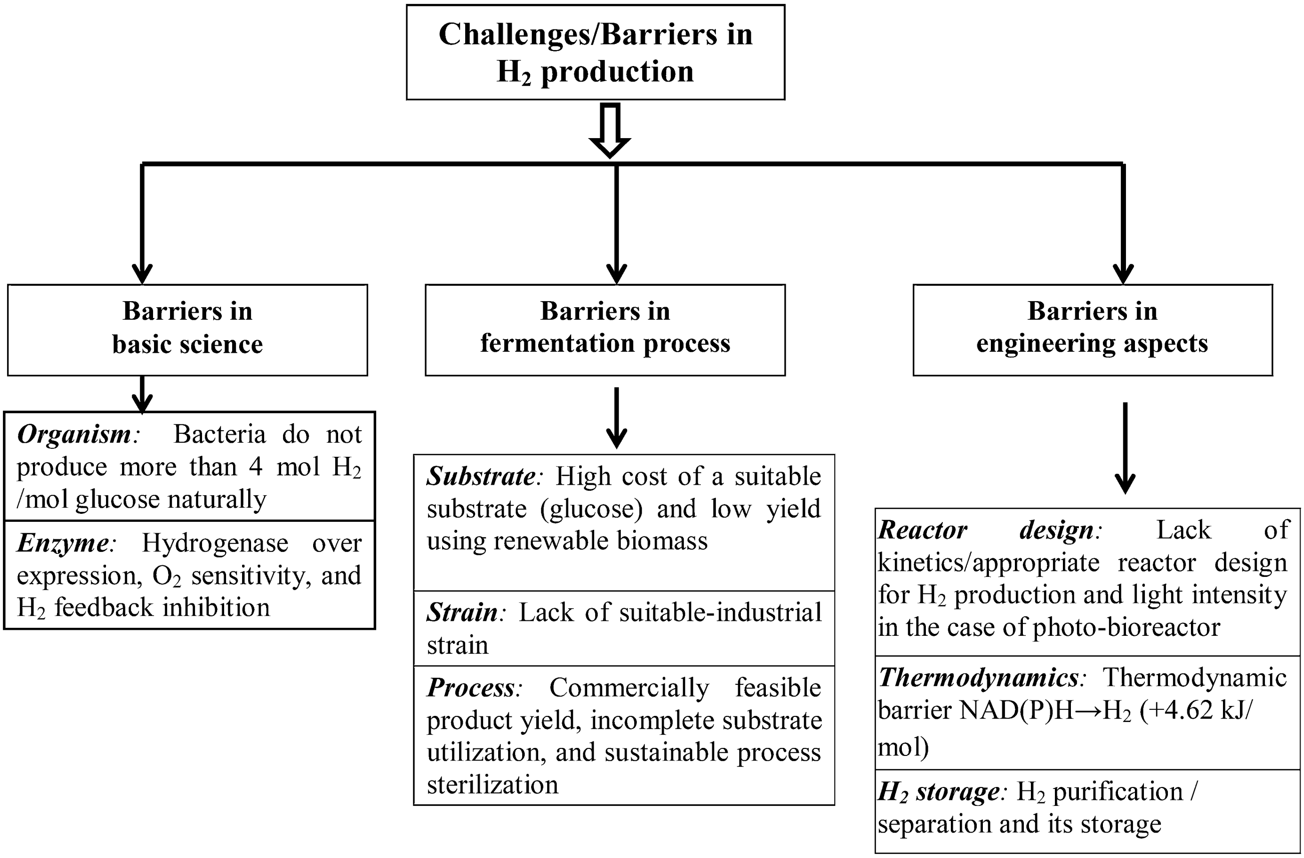
Forecasts with respect to the deficiency of fossil fuel reserves in the current century impose energy scientists to focus on alternative renewable energy sources. The advantage found in current biological processes explored for generating biohydrogen is the high efficiency of conversion of various biobased waste materials into hydrogen energy. This finding has encouraged the H_2 production processes via these routes. However, to shift the economy from fossil fuel dependence to H_2 energy-based, efforts are needed to rectify the demerits of H_2 production pathway toward optimizing the production processes. As per Momirlan and Veziroglu (2002), the confronting issues in biohydrogen generation and usage are its higher processing cost, transport, stockpiling, distribution and delivery, lower conversion rates, and rudimentary stage in consumer utilization etc. The challenges in H_2 production and selective biological production methods are depicted in Fig. 4 and Table 4, respectively.

Threats in hydrogen supply avenues for divergent transport systems bank on, to a large degree, the form of storage facility available on board. While considering conditioning of hydrogen, both compression and liquefaction are considered, as they are also viable on the context of commercial feasibility, but committed for ample advancements and improvements in this avenue, but these factors poise as emerging threat against the demand of H_2 as an attractive transportation fuel. Important demanding issues in the introduction of hydrogen during transport are depicted in Fig. 5.

Importance of biohydrogen generation in under developing countries

Energy intensity is measured simply as the ratio of gross domestic products (GDP) has fallen faster in non-Organization for Economic Co-operation and Development (OECD) countries. In the last decade, the OECD countries appraised for 52% of global energy consumption. This average per capita energy consumption in OECD countries is four times higher than non-OECD countries and seven times higher than Africa (IEA Energy statistics 2007; Ahuja and Tatsutani 2009). At least one-fourth of the global population is unable to enjoy the advantages of modern forms of energy. The average energy consumption per citizen in OECD countries is measured as 8365 kWh, which is significantly more compared to Asia (646 kWh) and African countries (563 kWh). Forty percentage of people in developing countries are inaccessible to electricity although 40–60 billion dollars are annually spent on harnessing and consumption of electricity in these countries. Providing basic electricity to these people at an average consumption level (50 kWh/person) would vastly impact the end-user demand. In low economic countries, limiting the demand for imported fuels and diversifying the domestic energy resource will invoke potential benefits. Biohydrogen-based energy can be a promising source of renewable energy technology to provide electricity at a minimal cost in low economic countries, wherever an extension of modern conversion technologies and process are implemented in a right manner (but can vary strongly with the impact of local conditions) (Ahuja and Tatsutani 2009).

However, biohydrogen generation in countries where inadequate economics prevail will impact societal norms like security on primary supply concerning the contribution for energy sufficiency, per capita GDP contribution, societal lifetime cost, etc. (Ren et al. 2013; Sun et al. 2010). Stanislaus et al. (2017) have reported that biohydrogen from digested sludge shows a positive energy balance. This indicated that biohydrogen can be a sustainable approach to reduce the negative impact of global warming with a low cumulative non-renewable energy demand. Singh et al. (2016) and Sekoai and Daramola (2015) suggested that hydrogen is the safest fuel due to its natures like non-toxicity and other positive attributes. Therefore, biohydrogen production is much needed in developing countries, because it is whispered that developing



(Bhutto et al. 2011; Kapdan and Kargi 2006; Das and Veziroglu 2001; Kotay and Das 2008; Hong et al. 2013)

Fig. 4 Challenges in H_2 production

Table 4 Major challenges in selective biological production

Major challenges in		
Biophotolysis	Photofermentation	Dark fermentation
High cost	High cost	Inefficient and costly pretreatment methods
Large surface area requirement	Needs a high intensity light	Incomplete substrate conversion
Formation of explosive gas mixer	Low photosynthetic conversion efficiency	Difficult fermentive substrate utilization
Expensive photobioreactors	Expensive bioreactors	Low chemical oxygen demand (COD) removal
Low H_2 productivity	Complex photobioreactor design	Difficult fermentive substrate utilization
Less than 10% solar energy utilization	Low productivity of nitrogenases	Incomplete substrate conversion
Oxygen intolerance H_2 producing enzymes	Problematic practical applications	
Problems in hydrogen recovery from reactor	Low solar energy utilization	
Low photosynthetic conversion efficiencies	Oxygen intolerant photobiological enzymes	

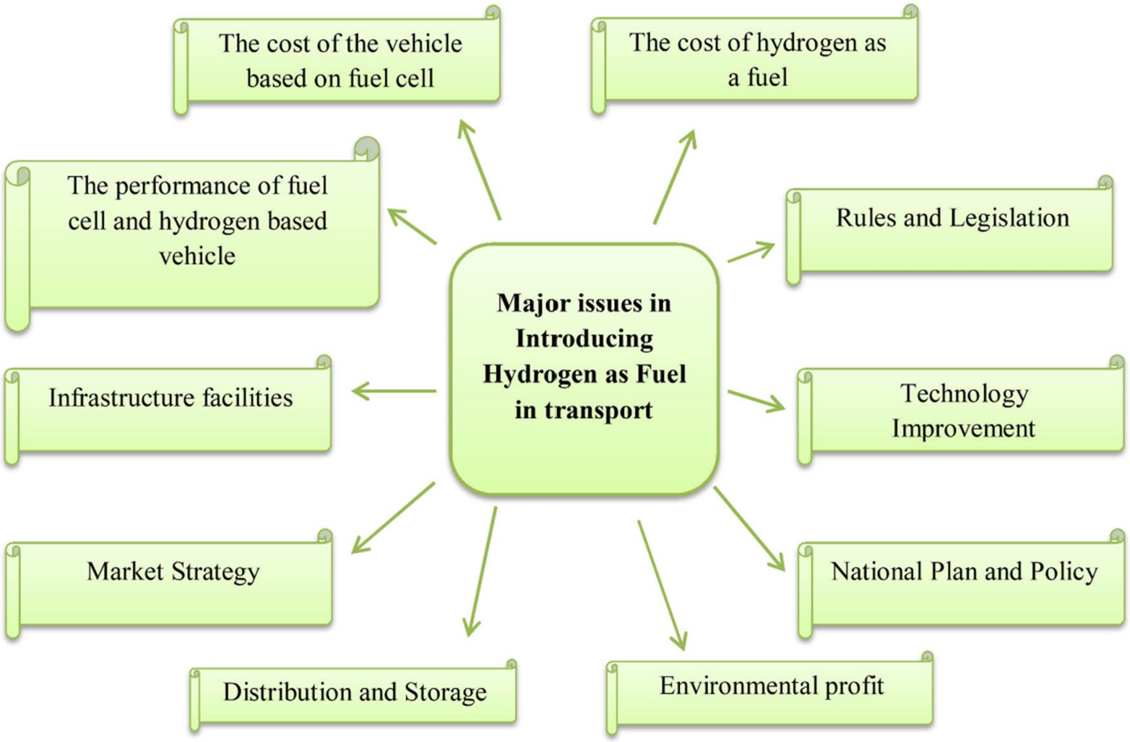


Fig. 5 Major issues in introducing hydrogen as fuel

countries are accounted for huge sharing of overall gas emissions and contribute to the negative environmental impacts (Ahuja and Tatsutani 2009). Also, biohydrogen will reduce the lifetime cost-competitive with gasoline vehicles in terms of vehicle retail cost, the externality cost of oil use, non-cost social transfers, etc. (Ogden et al. 2004; Rathore et al. 2019). This cost reduction will be a big boon impacting directly on the allocation of annual investment of countries, especially for low economic countries.

Future constraints of H_2 production

The world is witnessing a momentum in the development of technologies toward hydrogen energy generation. Harnessing hydrogen, dissemination, and utility have become important aspects of research, planning, and policy making. The carbon footprint impact of hydrogen from fossil fuel as well as other sources is more promising in comparison with conventional fuel processing (McLellan et al. 2005; Burmistrz et al. 2014). According to Derwent et al. (2006), substituting the fossil fuel dependence with biohydrogen would only have a climate impact on 0.6% of the current system. Numerous technologies can be used to produce hydrogen using primary energy sources (Balat and Kırtay 2010). High-throughput investigations impart a vital role in biohydrogen fermentation operations, in order to attain reliable data for scale-up studies. Novel reactor designs with high levels of parallelization combined with online computer systems are required to evaluate the acute process setting during the procedure. Aid of mathematical and statistical tools in biohydrogen fermentation mechanisms is also crucial to assist analysis on the synergistic effects of various factors on the overall yield (Sekoai and Daramola 2015).

Application of biological tools in hydrogen production is the prevailing threat for biotechnology emphasizing on the present and unknown future environmental concerns. The potential scope of biological mode of hydrogen generation is not only resolved by scientific overtures (e.g., the genetic alteration of microorganisms for competency enhancement, designing of bioreactor) but also by economics, societal acceptance and the progress in systems for hydrogen energy (Singh et al. 2017). Several researches have to be investigated on the context of environmentally sustainable energy forms substituting traditional fuels sourced through biomass and emerging organic wastes. Complete technology demonstrations are pivotal for hydrogen production from biomass to overcome major challenges to make economically competitive (Balat and Kırtay 2010). State-of-art blueprint such as boosting operation conditions like temperature, pH, OLR and HRT, bioreactor alterations, substrate choice, strain selection and nutrient enrichments, microbial immobilization and the metabolic construction of biohydrogen pathways, need to be channelized on enhancing biohydrogen procurement (Arimi et al. 2015; Soydemir et al. 2016). Development in fuel cell encourages rapid usage of hydrogen for domestic, thermal, industrial, and transport energy requirements. Nascent approaches are expected to emerge for hydrogen transformation, reduced rate, and cost when harnessed in industrial scale (Preethi et al. 2019).

Conclusion

Hydrogen in its free form is hardly unavailable in nature while comparing its counterparts; hence, the need for exploring new channels of the worthwhile generation of hydrogen. This review work comparatively evaluates and assesses preferred processes involving hydrogen harnessing methods against selected organic waste. Utilization of solid wastes like food waste, agricultural waste, animal waste, municipal waste, sewage waste, industrial waste, and wastewaters was found as attractive as well as feasible for biohydrogen production. Existing biohydrogen production processes are required to be modified for better fermentation, for unlocking new openings in biohydrogen production from renewable biomass. Large working reactor volumes, suitable tested environments, advanced technology, different storage, and transportation facilities are required to overcome the drawbacks like low yields and rate of hydrogen formation, while converting organic waste to biohydrogen. Developments in the field of biotechnology involving metagenomics approaches and genetic modifications are the recent technological advancements assist to make microbial assisted generation of hydrogen commercially viable, practical, and economically feasible in the near future. Although biohydrogen promises a lot as a potential fuel, further research and development of available current methodologies are the need of the hour, for improving the yield of biohydrogen and to validate its potential impacts, so as to consider hydrogen energy as a future sustainable energy source.

Acknowledgements The authors wish to thank all who assisted in conducting this work.

Funding The authors received no specific funding from any agency or organization toward making of this manuscript.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Ahmad T, Aadil RM, Ahmed H, Rahman UU, Soares BCV et al (2019) Treatment and utilization of dairy industrial waste: a review. Trends Food Sci Technol 88:361–372

Ahuja D, Tatsutani M (2009) Sustainable energy for developing countries. S A P I EN S 2:1–16

Alexandropoulou M, Antonopoulou G, Trably E, Carrere H, Lyberatos G (2018) Continuous biohydrogen production from a food industry waste: influence of operational parameters and microbial community analysis. J Cleaner Prod 174:1054–1063

Argun H, Gokfiliz P, Karapinar I (2017) Biohydrogen production potential of different biomass sources. In: Singh A, Rathore D (eds) Biohydrogen production: sustainability of current technology and future perspective. Springer India, New Delhi, pp 11–78

Arimi MM, Knodel J, Kiprop A, Namango SS, Zhang Y, Geiben SU (2015) Strategies for improvement of biohydrogen production from organic-rich wastewater: a review. Biomass Bioenergy 75:101–118

Arizzi M, Morra S, Pugliese M, Gullino ML, Gilardi G et al (2016) Biohydrogen and biomethane production sustained by untreated matrices and alternative application of compost waste. Waste Manag 56:151–157

Azbar N, Cetinkaya Dokgoz FT, Keskin T, Korkmaz KS, Syed HM (2009) Continuous fermentative hydrogen production from cheese whey waste water under thermophilic anaerobic conditions. Int J Hydrog Energy 34:7441–7447

Balachandar G, Khanna N, Das D (2013) Chapter-6: Biohydrogen production from organic wastes by dark fermentation. In: Panday A, Chang JS, Hallenbecka PC, Larroche C (eds) Biohydrogen. Elsevier, Amsterdam, pp 103–144

Balat H, Kırtay E (2010) Hydrogen from biomass. Present scenario and future prospects. Int J Hydrog Energy 35:7416–7426

Basak B, Fatima A, Jeon B, Ganguly A, Chatterjee PK et al (2018) Process kinetic studies of biohydrogen production by co-fermentation of fruit-vegetable wastes and cottage cheese whey. Energy Sustain Dev 47:39–52

Benemann JR (1997) Feasibility analysis of photobiological hydrogen production. Int J Hydrog Energy 22:979–987

Boni MR, Sbaffoni S, Tuccinardi L, Viotti P (2013) Development and calibration of a model for biohydrogen production from organic waste. Waste Manag 33:1128–1135

Burmistrz P, Chmielniak T, Czepirski L, Gazda-Grzywacz M (2014) Carbon footprint of the hydrogen production process utilizing subbituminous coal and lignite gasification. J Cleaner Prod 139:858–865

Cai J, Zhao Y, Fan J et al (2019) Photosynthetic bacteria improved hydrogen yield of combined dark- and photo-fermentation. J Biotechnol 302:18–25

Castillo-Hernandez A, Mar-Alvarez I, Moreno-Andrade I (2015) Start-up and operation of continuous stirred-tank reactor for biohydrogen production from restaurant organic solid waste. Int J Hydrog Energy 40:17239–17245

Chandrasekhar K, Lee Y, Lee D (2015) Biohydrogen production: strategies to improve process efficiency through microbial routes. Int J Mol Sci 16:8266–8293

Chatellard L, Marone A, Carrère H, Trably E (2017) Trends and challenges in biohydrogen productionfrom agricultural waste. In: Singh A, Rathore D (eds) biohydrogen production: sustainability of current technology and future perspective. Springer India, New Delhi, pp 69–95

Chen CC, Chuang YS, Lin CY, Lay CH, Sen B (2012) Thermophilic dark fermentation of untreated rice straw using mixed cultures for hydrogen production. Int J Hydrog Energy 37:15540–15546

Cheng J, Ding L, Lin R, Yue L, Liu J et al (2016) Fermentative biohydrogen and biomethane co-production from mixture of food waste and sewage sludge: effects of physiochemical properties and mix ratios on fermentation performance. Appl Energy 184:1–8

Chu Y, Wei Y, Yuan X, Shi X (2011) Bioconversion of wheat stalk to hydrogen by dark fermentation: effect of different mixed microflora on hydrogen yield and cellulose solubilisation. Bioresour Technol 102:3805–3809

Concetti S, Chiariotti A, Patriarca C, Marone A, Contò G et al (2013) Biohydrogen production from buffalo manure codigested with agroindustrial by-products in an anaerobic reactor. Buffalo Bull 32:1241–1244

da Silva AN, Macedo WV, Sakamoto IK, Pereyra DLAD, Mendes CO et al (2019) Biohydrogen production from dairy industry wastewater in an anaerobic fluidized-bed reactor. Biomass Bioenergy 120:257–264

Dareioti MA, Kornaros M (2014) Effect of hydraulic retention time (HRT) on the anaerobic co-digestion of agro-industrial wastes in a two-stage CSTR system. Bioresour Technol 167:407–415

Dareioti MA, Vavouraki AI, Kornaros M (2014) Effect of pH on the anaerobic acidogenesis of agroindustrial wastewaters for maximization of bio-hydrogen production: a lab-scale evaluation using batch tests. Bioresour Technol 162:218–227

Das D, Veziroglu TN (2001) Hydrogen production by biological processes: a survey of literature. Int J Hydrog Energy 26:13–28

Das D, Veziroglu TN (2008) Advances in biological hydrogen production processes. Int J Hydrog Energy 33:6046–6057

Das D, Khanna N, Veziroğlu NT (2008) Recent developments in biological hydrogen production processes. Chem Ind Chem Eng Q 14:57–67

Derwent R, Simmonds P, O'Doherty S, Manning A, Collins W, Stevenson D (2006) Global environmental impacts of the hydrogen economy. Int J Nucl Hydrog Prod Appl 1:57–67

Dinesh GK, Chauhan R, Chakma S (2018) Influence and strategies for enhanced biohydrogen production from food waste. Renew Sust Energy Rev 92:807–822

Dutta D, Debojyoti D, Chaudhuri S, Bhattacharya S (2005) Hydrogen production by cyanobacteria. Microb Cell Fact 4:36

El-Bery H, Tawfik A, Kumari S, Bux F (2013) Effect of thermal pretreatment on inoculum sludge to enhance bio-hydrogen production from alkali hydrolysed rice straw in a mesophilic anaerobic baffled reactor. Environ Technol 34:1965–1972

Esposito G, Frunzo L, Giordano A, Liotta F, Panico A et al (2012) Anaerobic co-digestion of organic wastes. Rev Environ Sci Biol Technol 11:325–341

FAO (2011) Global food losses and food waste- Eextent, causes and prevention. FAO, Rome

FAO (2013) FAO statistical yearbook 2013: world food and agriculture. FAO, Rome

Fernandes BS, Peixoto G, Albrecht FR et al (2010) Potential to produce biohydrogen from various wastewaters. Energy Sustain Dev 14:143–148

Gadhae A, Sonawane SS, Varma MN (2015) Enhanced biohydrogen production from dark fermentation of complex dairy wastewater by sonolysis. Int J Hydrog Energy 40:9942–9951

Gadhe A, Sonawane S, Verma MN (2014) Ultrasonic pretreatment for an enhancement of biohydrogen production from complex food waste. Int J Hydrog Energy 39:7721–7729

Ghimire A, Frunzo L, Pontoni L, d'Antonio G, Lens PNL et al (2015) Dark fermentation of complex waste biomass for biohydrogen production by pretreated thermophilic anaerobic digestate. J Environ Manag 152:43–48

Ghimire A, Luongo V, Frunzo LM, Pirozzi F, Lens PNL et al (2017) Continuous biohydrogen production by thermophilic dark fermentation of cheese whey: use of buffalo manure as buffering agent. Int J Hydrog Energy 42(8):4861–4869

Ghosh R, Bhadury P, Debnath M (2017) Characterization and screening of algal strains for sustainable biohydrogen production: primary constraints. In: Singh A, Rathore D (eds) Biohydrogen production: sustainability of current technology and future perspective. Springer India, New Delhi, pp 115–146

Gilroyed BH, Li C, Hao X, Chu A, McAllister TA (2010) Biohydrogen production from specified risk materials co-digested with cattle manure. Int J Hydrog Energy 35:1099–1105

Gorgec FK, Karapinar I (2019) Production of biohydrogen from waste wheat in continuously operated UPBR: the effect of influent substrate concentration. Int J Hydrog Energy 44:17323–17333

Greenbaum E, Guillard RRL, Sunda WG (1983) Hydrogen and oxygen photoproduction by marine algae. Photochem Photobiol 37:649–655

Gupta SK, Kumari S, Reddy K, Bux F (2013) Trends in biohydrogen production: major challenges and state of the art developments. Environ Technol 34:1653–1670

Hafez H, Nakhla G, El Naggar H (2009) Biological hydrogen production from corn-syrup waste using a novel system. Energies 2:445–455

Hallenbeck PC, Benemann JR (2002) Biological hydrogen production; fundamentals and limiting processes. Int J Hydrog Energy 27:1185–1193

Hamelers HVM, Ter-Heijne A, Sleutels THJA, Jeremiasse AW, Strik DPBTB, Buisman CJN (2010) New applications and performance of bio-electrochemical systems. Appl Microbiol Biotechnol 85:1673–1685

Han H, Wei L, Liu B, Yang H, Shen J (2012) Optimization of biohydrogen production from soybean straw using anaerobic mixed bacteria. Int J Hydrog Energy 37:13200–13208

Han W, Liu DN, Shi YW, Tang JH, Li YF et al (2015) Biohydrogen production from food waste hydrolysate using continuous mixed immobilized sludge reactors. Bioresour Technol 180:54–58

Han W, Huang J, Zhao H, Li Y (2016) Continuous biohydrogen production from waste bread by anaerobic sludge. Bioresour Technol 212:1–5

Holladay JD, Hu J, King DL, Wang Y (2009) An overview of hydrogen production technologies. Catal Today 139:244–260

Hong Y, Nizami AS, Pourbafrani M, Saville BA, MacLean HL (2013) Impact of cellulase production on environmental and financial metrics for lignocellulosic ethanol. Biofuels Bioprod Biorefin 7:303–313

Hsiao CL, Chang JJ, Wu JH, Chin WC, Wen FS et al (2009) Clostridium strain cocultures for biohydrogen production enhancement from condensed molasses fermentation solubles. Int J Hydrog Energy 34:7173–7181

Hu B, Li M, Wang Y, Zhu M (2018) High-yield biohydrogen production from non-detoxified sugarcane bagasse: fermentation strategy and mechanism. Chem Eng J 335:979–987

Huang CY, Hsieh H, Lay CH, Chuang YS, Kuo AY et al (2010) Biohydrogen production by anaerobic co-digestion of textile and food wastewaters. In: The 2010 Asian bio-hydrogen symposium and APEC advanced bio-hydrogen technology conference Taiwan

Hwang JH, Choi JA, Abou-Shanab RAI, Min B, Song H et al (2011) Feasibility of hydrogen production from ripened fruits by a combined two-stage (dark/dark) fermentation system. Bioresour Technol 102:1051–1058

IEA, Energy statistics, p. 6. http://www.iea.org/textbase/nppdf/free/2007/key_stats_2007.pdf. Accessed 6 Aug 2008

Jiang D, Ge X, Zhang T, Liu H, Zhang Q (2016) Photo-fermentative hydrogen production from enzymatic hydrolysate of corn stalk pith with a photosynthetic consortium. Int J Hydrog Energy 41:16778–16785

Jung KW, Kim DH, Shin SH (2010) Continuous fermentative hydrogen production from coffee drink manufacturing wastewater by applying UASB reactor. Int J Hydrog Energy 35:13370–13378

Kanchanasuta S, Prommeenate P, Boonapatcharone N, Pisutpaisal N (2017) Stability of *Clostridium butyricum* in biohydrogen production from non-sterile food waste. Int J Hydrog Energy 42:3454–3465

Kannah RY, Kavitha S, Sivashanmugam P, Kumar G, Nguyen DD et al (2019) Biohydrogen production from rice straw: effect of combinative pretreatment, modelling assessment and energy balance consideration. Int J Hydrog Energy 44:2203–2215

Kaushik A, Sharma M (2017) Exploiting biohydrogen pathways of cyanobacteria and green algae: an industrial production approach. In: Singh A, Rathore D (eds) Biohydrogen production: sustainability of current technology and future perspective. Springer India, New York, pp 97–114. https://doi.org/10.1007/978-81-322-3577-4_5

Kongjan P, O-Thong S, Angelidaki I (2013) Hydrogen and methane production from desugared molasses using a two-stage thermophilic anaerobic process. Eng Life Sci 13(2):118–125

Korres NE, Norsworthy JK (2017) Biohydrogen production from agricultural biomass and organic wastes. In: Singh A, Rathore D (eds) Biohydrogen production: sustainability of current technology and future perspective. Springer India, New Delhi, pp 79–86

Korres NE, O'Kiely P, Benzie JAH, West JS (2013) Bioenergy production by anaerobic digestion: using agricultural biomass and organic waste. Pub Earthscan from Routledge/Taylor and Francis Pub. Group, London

Kotay SM, Das D (2008) Biohydrogen as a renewable energy resource-Prospects and potentials. Int J Hydrogen Energy 33:258–263

Kotsopoulos TA, Fotidis IA, Tsolakis N, Martzopoulos GG (2009) Biohydrogen production from pig slurry in a CSTR reactor system with mixed cultures under hyperthermophilic temperature. Biomass Bioenergy 33:1168–1174

Koutrouli EC, Kalfas H, Gavala HN, Skiadas IV, Stamatelatou K et al (2009) Hydrogen and methane production through two-stage mesophilic anaerobic digestion of olive pulp. Bioresour Technol 100:3718–3723

Krupp M, Widmann R (2009) Biohydrogen production by dark fermentation: experiences of continuous operation in large lab scale. Int J Hydrog Energy 34:4509–4516

Kumar G, Nguyen DD, Sivagurunathan P, Kobayashi T, Xu K et al (2018) Cultivation of microalgal biomass using swine manure for biohydrogen production: impact of dilution ratio and pretreatment. Bioresour Technol 260:16–22

Kumar AN, Bandarapu AK, Venkata Mohan S (2019) Microbial electro-hydrolysis of sewage sludge for acidogenic production of biohydrogen and volatile fatty acids along with struvite. Chem Eng J 374:1264–1274

Lateef SA, Beneragama N, Yamashiro T, Iwasaki M, Ying C et al (2012) Biohydrogen production from codigestion of cow manure and waste milk under thermophilic temperature. Bioresour Technol 110:251–257

Lay JJ, Li YY, Noike T (1997) Influences of pH and moisture content on the methane production in high-solids sludge digestion. Water Res 31:1518–1524

Lay JJ, Lee YJ, Noike T (1999) Feasibility of biological hydrogen production from organic fraction of municipalsolid waste. Water Res 33:2579–2586

Lay CH, Kuo SY, Sen B, Chen CC, Chang JS et al (2012) Fermentative biohydrogen production from starch-containing textile wastewater. Int J Hydrog Energy 37:2050–2057

Lay C, Vo T, Lin P, Lin CY, Lee CW et al (2019) Anaerobic hydrogen and methane production from low-strength beverage wastewater. In press, Int J Hydrog Energy. https://doi.org/10.1016/j.ijhydene.2019.03.165

Lee D (2016) Cost-benefit analysis, LCOE and evaluation of financial feasibility of full commercialization of biohydrogen. Int J Hydrog Energy 41:4347–4357

Li C, Fang HHP (2007) Fermentative hydrogen production from wastewater and solid wastes by mixed cultures. Crit Rev Environ Sci Technol 37:1–39

Li Y, Zhnag Z, Zhu S et al (2018) Comparison of bio-hydrogen production yield capacity between asynchronous and simultaneous saccharification and fermentation processes from agricultural residue by mixed anaerobic cultures. Bioresour Technol 247:1210–1214

Lin CY, Lay CH (2004) Carbon/nitrogen-ratio effect on fermentative hydrogen production by mixed microfora. Int J Hydrog Energy 29:41–45

Liu H, Grot S, Logan BE (2005) Electrochemically assisted microbial production of hydrogen from acetate. Environ Sci Technol 39:4317–4320

Liu Z, Li Q, Zhang C, Wang L, Han B et al (2014) Effects of operating parameters on hydrogen production from raw wet steam-exploded cornstalk and two-stage fermentation potential for biohythane production. Biochem Eng J 90:234–238

Lopez-Hidalgo AM, Sanchez A, León-Rodríguez A (2017) Simultaneous production of bioethanol and biohydrogen by *Escherichia coli* WDHL using wheat straw hydrolysate as substrate. Fuel 188:19–27

Lopez-Hidalgo AM, Alvarado-Cuevas ZD, Leon-Rodriguez A (2018) Biohydrogen production from mixtures of agro-industrial wastes: chemometric analysis, optimization and scaling up. Energy 159:32–41

Lu C, Wang Y, Lee D, Zhang H, Tahir N et al (2019) Biohydrogen production in pilot-scale fermenter: effects of hydraulic retention time and substrate concentration. J Clean Prod 229:751–760

Mahmod SS, Azahar AM, Tan JP, Jahim JMD, Abdul PM et al (2019) Operation performance of up-flow anaerobic sludge blanket (UASB) bioreactor for biohydrogen production by self-granulated sludge using pre-treated palm oil mill effluent (POME) as carbon source. Renew Energy 134:1262–1272

Manoharan Y, Hosseini SE, Butler B, Alzhahrani H, Senior BTF et al (2019) Hydrogen fuel cell vehicles; current status and future prospect. Appl Sci 9:2296

Marone A, Izzo G, Mentuccia L, Massini G, Paganin P et al (2014) Vegetable waste as substrate and source of suitable microflora for bio-hydrogen production. Renew Energy 68:6–13

Marone A, Varrone C, Fiocchetti F, Giussani B, Izzo G et al (2015) Optimization of substrate composition for biohydrogen production from buffalo slurry co-fermented with cheese whey and crude glycerol, using microbial mixed culture. Int J Hydrog Energy 40:209–218

McLellan B, Shoko E, Dicks AL, Da Costa JD (2005) Hydrogen production and utilisation opportunities for Australia. Int J Hydrog Energy 30:669–679

Menetrez MY (2012) An overview of algae biofuel production and potential environmental impact. A critical review. Environ Sci Technol 46:7073–7085

Menon V, Rao M (2012) Trends in bioconversion of lignocellulose: biofuels, platform chemicals and biorefinery concept. Prog Energy Combust Sci 38:522–550

Miandad R, Rehan M, Ouda OKM, Khan MZ, Shahzad K et al (2017) Waste-to-hydrogen energy in Saudi Arabia: challenges and perspectives. In: Singh A, Rathore D (eds) Biohydrogen production: sustainability of current technology and future perspective. Springer India, New York, pp 237–252

Miller A, Singh L, Wang L, Liu H (2019) Linking internal resistance with design and operation decisions in microbial electrolysis cells. Environ Int 126:611–618

Mirza SS, Qazi JI, Liang Y, Chen S (2019) Growth characteristics and photofermentative biohydrogen production potential of purple non sulfur bacteria from sugar cane bagasse. Fuel 255:115805

Mishra P, Balachandar G, Das D (2017) Improvement in biohythane production using organic solid waste and distillery effluent. Waste Manag 66:70–78

Mishra P, Ameen F, Zaid RM, Singh L, Ab Wahid Z et al (2019) Relative effectiveness of substrate-inoculum ratio and initial pH on hydrogen production from palm oil mill effluent: kinetics and statistical optimization. J Clean Prod 228:276–283

Momirlan M, Veziroglu TN (2002) Current status of hydrogen energy. Renew Sustain Energy Rev 6:141–179

Momirlan M, Veziroglu TN (2005) The properties of hydrogen as fuel tomorrow in sustainable energy system for a cleaner planet. Int J Hydrog Energy 30:795–802

Monlau F, Sambusiti C, Barakat A, Guo XM, Latrille E et al (2012) Predictive models of biohydrogen and biomethane production based on the compositional and structural features of lignocellulosic materials. Environ Sci Technol 46:12217–12225

Nagarajan D, Lee D, Chang J (2019) Recent insights into consolidated bioprocessing for lignocellulosic biohydrogen production. Int J Hydrog Energy 44:14362–14379

Nasirian N, Almassi M, Minaei S, Widmann R (2011) Development of a method for biohydrogen production from wheat straw by dark fermentation. Int J Hydrog Energy 36:411–420

Nicolet Y, Fontecilla-Camps JC, Fontecava M (2010) Maturation of [FeFe]-hydrogenases: structures and mechanisms. Int J Hydrog Energy 35:10750–10760

Nikolaidis P, Poullikkas A (2017) A comparative overview of hydrogen Production processes. Renew Sustain Energy Rev 67:597–611

Oceguera-Contreras E, Aguilar-Juarez O, Oseguera-Galindo D et al (2019) Biohydrogen production by vermihumus-associated microorganisms using agro industrial wastes as substrate. Int J Hydrog Energy 44:9856–9865

Oey M, Sawyer AL, Ross IL, Hankamer B (2016) Challenges and opportunities for hydrogen production from microalgae. Plant Biotechnol J 14:1487–1499

Ogden JM, William RH, Larson ED (2004) Societal lifecycle cost comparison of cars with alternative fuels/engines. Energy Policy 32:7–27

Ozkan L, Erguder TH, Demirer GN (2011) Effects of pretreatment methods on solubilization of beet-pulp and bio-hydrogen production yield. Int J Hydrog Energy 36:382–389

Panigrahi S, Dubey BK (2019) A critical review on operating parameters and strategies to improve the biogas yield from anaerobic digestion of organic fraction of municipal solid waste. Renew Energ 143:779–797

Patel AK, Vaisnav N, Mathur A, Gupta R, Tuli DK (2016) Whey waste as potential feedstock for biohydrogen production. Renew Energy 98:221–225

Perera KRJ, Nirmalakhandan N (2010) Enhancing fermentative hydrogen production from sucrose. Bioresour Technol 101:9137–9143

Preethi Usman TMM, Banu R, Gunasekaran M, Kumar G (2019) Biohydrogen production from industrial wastewater: an overview. Bioresour Technol Rep 7:100287

Quéméneur M, Bittel M, Trably E, Dumas C, Fourage L et al (2012) Effect of enzyme addition on fermentative hydrogen production from wheat straw. Int J Hydrog Energy 37:10639–10647

Rafieenia R, Pivato A, Lavagnolo MC (2019) Optimization of hydrogen production from food waste using anaerobic mixed cultures pretreated with waste frying oil. Renew Energy 139:1077–1085

Rathore D, Singh A, Dahiya D, Nigam PS (2019) Sustainability of biohydrogen as fuel: present scenario and future Perspective. AIMS Energy 7:1–19

Ren N, Wang A, Cao G, Xu J, Gao L (2009) Bioconversion of lignocellulosic biomass to hydrogen: potential and challenges. Biotechnol Adv 27:1051–1060

Ren J, Manzardo A, Toniolo S, Toniolo S, Scipioni A (2013) Sustainability of hydrogen supply chain. Part I: identification of critical criteria and cause-effect analysis for enhancing the sustainability using DEMATEL. Int J Hydrog Energy 38:14159–14171

Ren H, Kong F, Zhao L, Ren NQ, Ma J et al (2019) Enhanced co-production of biohydrogen and algal lipids from agricultural biomass residues in long-term operation. Bioresour Technol 289:121774

Roy S, Ghosh S, Das D (2012) Improvement of hydrogen production with thermophilic mixed culture from rice spent wash of distillery industry. Int J Hydrog Energy 37:15867–15874

Saidi R, Liebgott PP, Gannoun H, Gaida LB, Miladi B et al (2018) Biohydrogen production from hyperthermophilic anaerobic digestion of fruit and vegetable wastes in seawater: simplification of the culture medium of *Thermotoga maritima*. Waste Manag 71:474–484

Salem AH, Brunstermann R, Mietzel T, Widmann R (2018) Effect of pre-treatment and hydraulic retention time on biohydrogen production from organic wastes. Int J Hydrog Energy 43:4856–4865

Sekoai PT, Daramola MO (2015) Biohydrogen production as a potential energy fuel in South Africa. Biofuel Res J 2:223–226

Sen B, Aravind J, Kanmani P, Lay C (2016) State of the art and future concept of food waste fermentation to bioenergy. Renew Sustain Energy Rev 53:547–557

Shi X, Song H, Wang C, Tang R, Huang Z et al (2010) Enhanced bio-hydrogen production from sweet sorghum stalk with alkalization pretreatment by mixed anaerobic cultures. Int J Energy Res 34:662–672

Silva-Illanes F, Tapia-Venegas E, Schiappacasse MC, Trably E, Ruiz-Filippi G (2017) Impact of hydraulic retention time (HRT) and pH on dark fermentative hydrogen production from glycerol. Energy 141:358–367

Singh A, Rathore D (2017) Biohydrogen: next generation fuel biohydrogen production: sustainability of current technology and future perspective. Springer India, New Delhi, pp 1–10

Singh S, Jain S, Venkateswaran PS, Tiwari AK, Nouni MR et al (2016) Hydrogen: a sustainable fuel for future of the transport sector. Renew Sust Energ Rev 51:623–633

Singh R, Singh A, Rathore D (2017) Biohydrogen: global trend and future perspective. In: Singh A, Rathore D (eds) Biohydrogen production: sustainability of current technology and future perspective. Springer India, New Delhi, pp 291–315

Sivaramakrishna D, Sreekanth D, Sivaramakrishnan M, Kumar BS, Himabindu V et al (2014) Effect of system optimizing conditions on biohydrogen production from herbal wastewater by slaughterhouse sludge. Int J Hydrog Energy 39:7526–7533

Sorathiya LM, Fulsoundar AB, Tyagi KK, Patel MD, Singh RR (2014) Eco-friendly and modern methods of livestock waste recycling for enhancing farm profitability. Int J Recycl Org Waste Agric 3:50

Soydemir G, Keris-Sen UD, Sen U, Gurol MD (2016) Biodiesel production potential of mixed microalgal culture grown in domestic wastewater. Bioproc Biosyst Eng 39:45–51

Staffell I, Scamman D, Abad AV, Balcombe P, Dodds PE et al (2019) The role of hydrogen and fuel cells in the global energy system. Energy Environ Sci 12:463–491

Stanislaus MS, Zhang N, Zhao C, Zhu Q, Li D, Yang Y (2017) *Ipomoea aquatica* as a new substrate for enhanced biohydrogen production by using digested sludge as inoculum. Energy 118:264–271

Suksong W, Kongjan P, O-Thong S (2015) biohythane production from co-digestion of palm oil mill effluent with solid residues by two-stage solid state anaerobic digestion process. Energy Procedia 79:943–949

Sun Y, Ogden J, Delucchi M (2010) Societal lifetime cost of hydrogen fuel cell vehicles. Int J Hydrog Energy 35:11932–11946

Sydney EB, Novak AC, Rosa D, Medeiros ABP, Brar S et al (2018) Screening and bioprospecting of anaerobic consortia for biohydrogen and volatile fatty acid production in a vinasse based medium through dark fermentation. Process Biochem 67:1–7

Tang GL, Huang J, Sun ZJ, Tang QQ, Yan CH et al (2008) Biohydrogen production from cattle wastewater by enriched anaerobic mixed consortia: influence of fermentation temperature and pH. J Biosci Bioeng 106:80–87

Tenca A, Schievano A, Perazzolo F, Adani F, Oberti R (2011) Biohydrogen from thermophilic cofermentation of swine manure with fruit and vegetable waste: maximizing stable production without pH control. Bioresour Technol 102:8582–8588

Tu W, Hallett JP (2019) Recent advances in the pretreatment of lignocellulosic biomass. Curr Opin Green Sustain Chem. https://doi.org/10.1016/j.cogsc.2019.07.004

Vatsala TM, Raj SM, Manimaran A (2008) A pilot-scale study of biohydrogen production from distillery effluent using defined bacterial co-culture. Int J Hydrog Energy 33:5404–5415

Venkata Mohan S, Pandey A (2013) Biohydrogen production: an introduction. In: Larroche AP-SCCH (ed) Biohydrogen. Elsevier, Amsterdam, pp 1–24

Venkata Mohan S, Chandrasekhar K, Chiranjeevi P, Suresh Babu P (2013) Chapter 10—Biohydrogen production from wastewater. In: Larroche AP-SCCH (ed) Biohydrogen. Elsevier, Amsterdam, pp 223–257

Voet D, Voet JG, Pratt CW (1999) Fundamentals of biochemistry. Wiley, New York, p 382

Walsh B, Ciais P, Janssens IA, Penuelas J, Riahi K et al (2017) Pathways for balancing CO_2 emissions and sinks. Nat Commun 8, Article number: 14856

Wang J, Yin Y (2018) Fermentative hydrogen production using various biomass-based materials as feedstock. Renew Sustain Energy Rev 92:284–306

Wang A, Ren N, Shi Y, Lee DJ (2008a) Bioaugmented hydrogen production from microcrystalline cellulose using co-culture: *Clostridium acetobutyricum* X9 and *Ethanoligenens harbinense* B49. Int J Hydrog Energy 33:912–917

Wang B, Li YQ, Wu N, Lan CQ (2008b) CO_2 bio- mitigation using microalgae. Appl Microbiol Biotechnol 79:707–718

Wang J, Xu S, Xiao B, Xu M, Yang L et al (2013) Influence of catalyst and temperature on gasification performance of pig compost for hydrogen-rich gas production. Int J Hydrog Energy 38:14200–14207

Willquist K, Pawar SS, Van Niel EW (2011) Reassessment of hydrogen tolerance in *Caldicellulosiruptor saccharolyticus*. Microb Cell Fact 10:111

Wu X, Yao W, Zhu J (2010) Effect of pH on continuous biohydrogen production from liquid swine manure with glucose supplement using an anaerobic sequencing batch reactor. Int J Hydrog Energy 35:6592–6599

Wu X, Lin H, Zhu J (2013) Optimization of continuous hydrogen production from co-fermenting molasses with liquid swine manure in an anaerobic sequencing batch reactor. Bioresour Technol 136:351–359

Xing Y, Li Z, Fan Y, Hou H (2010) Biohydrogen production from dairy manures with acidification pretreatment by anaerobic fermentation. Environ Sci Pollut Res Int 17:392–399

Yang G, Hu Y, Wang J (2019) Biohydrogen production from co-fermentation of fallen leaves and sewage sludge. Bioresour Technol 285:121342

Yokoi H, Maki R, Hirose J, Hayashi S (2002) Microbial production of hydrogen from starch manufacturing wastes. Biomass Bioenergy 22:89–95

Yokoyama H, Waki M, Moriya N, Yasuda T, Tanaka Y et al (2007) Effect of fermentation temperature on hydrogen production from cow waste slurry by using anaerobic microflora within the slurry. Appl Microbiol Biotechnol 74:474–483

Yoon JH, Sim SJ, Kim MS, Park TH (2002) High cell density culture of *Anabaena variabilis* using repeated injections of carbon dioxide for the production of hydrogen. Int J Hydrog Energy 27:1265–1270

Zhang ML, Fan YT, Xing Y, Pan CM, Zhang GS et al (2007a) Enhanced biohydrogen production from cornstalk wastes with acidification pretreatment by mixed anaerobic cultures. Biomass Bioenergy 31:250–254

Zhang R, El-Mashad HM, Hartman K, Wang F, Liu G et al (2007b) Characterization of food waste as feedstock for anaerobic digestion. Bioresour Technol 98:929–939

Zhang T, Jiang D, Zhang H, Jing Y, Tahir N et al (2019) Comparative study on bio-hydrogen production from corn stover: photo-fermentation, dark-fermentation and dark-photo co-fermentation. Int J Hydrog Energy. https://doi.org/10.1016/j.ijhydene.2019.04.170

Zhu GF, Wu P, Wei QS, Lin J, Gao YL et al (2010) Biohydrogen production from purified terephthalic acid (PTA) processing wastewater by anaerobic fermentation using mixed microbial communities. Int J Hydrog Energy 35:8350–8356