Biohydrogen production from anaerobic digestion and its potential as renewable energy

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Abstract

The current demand-supply scenario for fossil fuels requires an alternative energy source with cleaner combustion products whilst production of hydrogen from anaerobic digestion involves the utilization of waste materials and zero emission of greenhouse gasses. However, large scale industrial application has yet not been implemented due to numerous challenges in its production, storage, and transportation. This review study demonstrates that production of hydrogen from anaerobic digestion is potentially a worthy alternative regarding energy density, environmental impact, and cost. Moreover, dependence on fossil fuel systems in the future could be minimized when biohydrogen production is feasible from renewable energy sources.

Keywords Biohydrogen, hydride, volatile fatty acids, biomass, renewable energy, anaerobic digestion

1. Introduction

1.1 Background

The world is looking for sustainable energy sources in order to replace the continuous depletion of fossil fuel reserve and exponential rise in energy demand. Hydrogen could be considered a worthy alternative to conventional fossil fuel energy sources due to its high energy density (143 MJ kg^{-1}) [1] and clean combustion product (water vapor only) [2, 3]. Unfortunately, some technical issues have hindered the application of this technology on an industrial scale. These include process operation storage and transportation [4], cost of production [2] and process optimization [5-7]. As raw materials, fossil fuels are utilized in conventional methods of hydrogen production such as steam reforming of natural gas, partial oxidation of hydrocarbon or coal gasification [8]. None of these processes, however, are cost-effective because they involve both the utilization of fossil fuels and have a destructive impact on the environment by producing greenhouse gasses. Abbasi and Abassi [2] noted that 2.5–5 tones of CO_2 emission per ton of hydrogen is produced from fossil fuel sources. Hydrogen production from biomass is a renewable source of energy which is both sustainable and furthermore the combustion product poses no danger to the environment. Over the past few years, the anaerobic digestion process has the major focus of producing methane containing biogas from waste materials [9-11]. Recent studies have proven the technical feasibility to produce volatile fatty acid (VFA) and biohydrogen from anaerobic digestion [12-16]. Although such technical feasibility has been proven, biohydrogen production from anaerobic digestion has to date not been employed in large scale industrial production.

The aim of this literature review is to focus on the major challenges involved in biohydrogen production from anaerobic digestion [17-21]. However, there have been some reasons put forward why the industrial production of biohydrogen is not yet feasible. These challenges include sustainability in the production from different substrates, identifying the process inhibition conditions and avoiding them, optimizing common process parameters and finally the safety and economic challenges involved in creating a hydrogen storage system. Different bioreactor design and arrangements have been employed for biohydrogen production. The bioreactor arrangement along with process operating conditions (with different types of substrates) has been noted. The second part of the literature review includes the potential of biohydrogen as an alternative energy source. It includes the availability of fossil fuels in contrast to the current demand scenario, energy density and other fuel properties of hydrogen compared to common fossil fuels, the impact on the environment and overall cost comparison of biohydrogen production compared to conventional energy sources. Previous review articles discuss the potential of hydrogen as fuel, but to the best of our knowledge this is the first review study that focuses on: firstly, the production challenges of anaerobic biohydrogen production; and secondly, the potential of this fuel to be better than conventional energy sources.

1.2 Technical overview

Anaerobic digestion is a series of biochemical reactions by which organic materials are converted into a mixture of methane and carbon dioxide by microorganisms in the absence of oxygen [22]. The process includes four different stages, namely hydrolysis, acidogenesis, acetogenesis and the final stage of methanogenesis [23].

The initial stage of hydrolysis involves the transformation of insoluble organic materials in the substrate into their soluble derivatives. Compounds with higher molecular mass such as cellulose, hemicellulose, polysaccharides, proteins, and fats are converted into amino acids, sugars and fatty acids [24]. Extracellular enzymes secreted by different types of microorganisms enable the biodegradation of large molecules during this stage [22].

Acidogenesis is referred as the hydrogen production stage derived from anaerobic digestion. During this phase, the monomers and soluble derivatives of organic component in the substrate are converted into short chain volatile fatty acids (VFAs), hydrogen, carbon dioxide, alcohols and acetates [25]. According to different microbial proportions, acidogenic fermentation could be classified into three different types [26]. The butyric-type fermentation produces butyric acid and acetic acid along with CO_2 and H_2. Propionic-type fermentation involves no significant CO_2 and H_2 production in the production of propionic acid, acetic acid, and valeric acid. Finally, ethanol-type fermentation has major production components of ethanol and acetic acid along with small amounts of CO_2 and H_2 [26].

The products from the initial two stages cannot be consumed directly by the methanogens in the final stage. They are converted into acetate, hydrogen and carbon dioxide in the third stage of the anaerobic process [22]. The third stage of acetogenesis plays a critical role in biohydrogen production since the volatile fatty acids produced in the first two stages are converted into acetate and hydrogen. During this process, the final electron acceptors are protons that are eventually converted back into hydrogen after receiving electrons [27]. Bundhoo and Mohee. [28] reported that a high concentration of hydrogen in this stage inhibits the conversion of long chain fatty acids. The authors also contended that high partial pressure of hydrogen causes a metabolic shift in the production of lactate, ethanol, acetone and butanol. Later, Hydrogen is consumed during the conversion of ethanol to acetic acid where high partial pressure of hydrogen is thermodynamically favorable [29].

The final stage of anaerobic digestion involves the production of methane and carbon dioxide by methanogenic Achaea. Two different groups of microorganisms are operating during this stage. The acetotrophic group of methanogens consumes the acetates and converts them into methane and carbon dioxide while the hydrogenotrophic group converts hydrogen and carbon dioxide into methane [30]. The hydrogenotrophic group of methanogens consumes the hydrogen produced as an electron donor for the reduction of carbon dioxide [31]. During anaerobic biohydrogen production, the hydrogenotrophic group of methanogens acts as the hydrogen consumer in the final stage. Their activities are required to be supressed to ensure maximum biohydrogen production based on the anaerobic process.

2. Bioreactors for biohydrogen production

The technology involved in biohydrogen production has been evolving, and different types of bioreactors with varied arrangements have produced feasible results. Some research attempts have successfully tested the technical feasibility of biohydrogen production through anaerobic digestion. Table 1 summarizes the type of bioreactor arrangements, relevant process operating conditions, maximum biohydrogen production rate, and the yield from each process.

Table 1: Different types of bioreactors for biohydrogen production

Substrate	Operating conditions	Type of bioreactor	Maximum biohydrogen production rate	Maximum biohydrogen yield	Reference
Cheese whey	-	Batch Fermenter	6.35 ± 0.2 mol-H_2/mol-lactose	-	[18]
Food waste	35± 1˚C	STR	1.67 - 1.73	-	[17]

	pH = 6.0 ± 6.9		H_2/mol-hexose		
Anaerobic sludge	70˚C pH = 7.0-8.0	CSTR	1.11 mol-H_2/mol-hexose	-	[32]
Municipal sewage glucose	37˚C pH = 5.0	UASB	1.44 ± 0.1 mol-H_2/mol-hexose	-	[33]
Activated sludge	35± 1˚C	ESBG	1.7 mol-H_2/mol-hexose		[34]
Heat-treated sludge	35˚C pH = 5.5	ASBR	0.79 ± 0.03 mol-H_2/mol-hexose	-	[35]
Tofu-processing waste	60˚C pH = 5.5	CSTR	500 ml H_2 L^{-1} h^{-1}	2.3 mol H_2/mol glucose	[36]
Municipal wastes	pH = 4.65–5.87	TBSBR	67.67 ml H_2 L^{-1} h^{-1}	1.67 mol H_2/mol glucose	[19]
Cow dung compost	33.5˚C pH = 5	CSTBR	-	2.15 mol H_2/mol glucose	[37]
Clostridium butyricum (glucose)	37˚C pH = 5	Anaerobic continuous stirred tank reactor (ACSTR)	-	1.3 mol H2/mol glucose	[38]
Wastewater (glucose)	37˚C pH = 5.5	Anaerobic sequencing batch reactor (ASBR)	-	2.89 ± 0.18 mol H_2/mol glucose	[39]

Municipal sewage	40˚C	Fluidized bed reactor (FBR)	1800 ml H_2 L^{-1} h^{-1}	4.26+/- 0.04 mol H_2/mol sucrose	[40]
Activated sludge	55˚C pH = 7.0	Batch	-	1.25 mol H_2/mol glucose	[41]
Anaerobic digested sludge (from distillery wastewater)	37˚C pH = 5.5	Batch	-	1000 ml H_2/L medium	[42]
Clostridium butyricum CGS2 (starch)	37˚C pH = 5.5	CSTR	-	2.3 mol H_2/mol hexose	[43]

Immobilized bioprocess system has proven to be useful to enhance the production of biohydrogen through dark fermentation. For example, an yield of 2.1 mol/mol glucose was achieved in batch operation from waste wheat. The bioreactor assembly included a metal mesh assembly with covered plastic scouring sponge [44]. Another experiment showed 1.50 mol H_2/mol glucose yield of biohydrogen during batch fermentation [45]. Using corn stalk as carrier, this immobilized mixed culture technology produced 62.5 % yield compared to the suspended fermentation. Another experiment performed by Bai et al. [46] achieved a yield of 1.8 mol-H_2/mol-hexose by performing immobilization technology on a thin film and attached on a carrier by polymer.

More recent approaches includ the combination of Bio Electrochemical Systems (BES) and anaerobic digestion to produce biohydrogen [47, 48]. The Microbial Electrolysis Cell (MEC) method has the advantages of no downstream processing for hydrogen purification and low energy requirement (0.6 - 1 kWh/m^3H_2) compared to the conventional energy input for electrolysis (4.5–50.6 kWh/m^3 H_2) [49]. The process also makes it possible to completely recover produced biohydrogen and a higher yield (up to 8.55 mol H_2/mol-glucose at 0.6 V) [50] compared to 4 mol H_2/mol-glucose from dark fermentation [49].

Wu et al. [50] in their study used a single-chamber microbial electrolysis cell (MEC) to produce hydrogen using the effluent from an anaerobic baffled reactor (ABR). Their results included an impressive 99.0 ± 0.3% total COD removal efficiency, 1.31 ± 0.04 m^3H_2/m^3d hydrogen production, 2.78 ± 0.11 mLH_2/mg COD hydrogen yield and 138.63 ± 3.11% electrical energy efficiency. Other research studies have included a combination of MEC and MFC (Microbial Fuel Cell) in hydrogen production where MFC supplies the power required to operate the MEC. The following table (Table 2) includes MEC-MFC packages designed to treat the effluent from upstream processes that are not suitable to achieve the maximum hydrogen production rate and yield. This table lists the recent Bioelectrochemical system (BES) that has been developed for biohydrogen production.

Table 2: Bioelectrochemical system (BES) integration for different processes. (Modified from [52])

Feedstock	**Design**	**Description**	**Results**	**Additional Information**	**Refere nces**
Synthetic wastewater	BioH_2-MFC	Hydrogen-producing biofermenter (HPB)(2 L) + MFC (single chamber type, 100 mL)	Fermentation: 2.85 mol H_2 mol^{-1} glucos e, MFC: Maximum energy recovery, 559 J/L and	Integrated system for biohydrogen and effluent polishing with MFC	[53]

			removal efficiency of 97%		
Vegetable wastewater	BioH_2-MFC	Acidogenic sequencing batch biofilm reactor + MFC	Maximum power density 111.76 mW/m^2. Hydrogen production 2.46 mmol H_2 h^{-1}	80% of VFA consumed in MFC	[54]
Molasses wastewater	BioH_2-MEC	Ethanol-type batch fed dark fermentation +MEC	1.41 ± 0.08 m^3 H_2m^{-3} reactor/d at 0.6 V	Integrated Bio H_2 effluent (~3250 mg C OD L^{-1}) generated hydrogen	[55]
Synthetic media with acetate (100 mM of phosphate buffer)	MEC-MFC coupled system	MEC: two-chamber (450 mL each) MFC: single chamber (350 mL)	H_2 production rate 14.9 ± 0.4 mL L^{-1} d^{-1} and yield 1.60 ± 0.08 mol-H_2 mol-acetate^{-1}	MFC provided external power for MEC	[56]

The synergy of a MEC-bioreactor combined system offers maximum utilization of organic content in the substrate, and theoretically, it could achieve production up to 12 mol H_2/per mol glucose [57]. Not many research studies have been done using combined bioreactor arrangement with MEC. Furthermore, most industrial treatment processes can not ensure the same type and composition of waste materials for anaerobic digestion. Consequently, a generic model of anaerobic digestion should be designed using a suitable microbial strain, and metabolic pathway for high hydrogen yield. In this regard, the knowledge obtained from specific bioreactor arrangements and specic treatment processes could be employed in the generic model. More research initiatives are needed for the generic model where the emphasis is on anaerobic hydrogen production.

3. Challenges facing biohydrogen production

3.1 Sustainability in biohydrogen production from different substrates

The carbon content in different types of waste materials differs widely, and so does the biohydrogen production yield. A variable rate and yield cannot necessarily ensure sustainability in production. The biohydrogen production rate and yield also differ from anaerobic processes [58-62]. Table 3 summarizes the highest hydrogen yields derived from various types of biomass.

Table 3: Biohydrogen production from different substrates

Biomass	**Inoculum**	**Operating conditions**	**Highest H_2 yield**	**Highest H_2 production rate**	**Reference**
Cornstalk	Aerated microbial consortium	Pre-treating microbe additives (25 °C, 15 days)	176 mL H_2 g^{-1} DB	18 mL H_2 g^{-1} DB h^{-1}	[63]
Lawn grass	Mixed culture dominated by *C. pasteurianu*	Pre-Treating 4% HCl (30 min, boiling)	72.21 mL H_2 g^{-1} DB	1.72 mL H_2 g^{-1} DB h^{-1}	[14]

	m				
Sugarcane bagasse	*C. butyricum*	0.5% H_2SO_4(60 min,121 °C, 1.47 bar)	44 mL H_2 mmol^{-1} TS^{a}	4.7 mL H_2 h^{-1}	[64]
Rice straw	*T. neapolitana*	10% NH_4OH (60 min, 121 °C) and 1% H_2SO_4 (50 min, 121 °C)	77.1 mL H_2 g^{-1} DB^{d}	0.19 mL H_2 h^{-1}	[65]
Corn stalk	*T. thermosaccharolyticum*W16	60°C Batch	89.3 mL H_2 g^{-1} dry biomass	-	[66]
Wheat straw	*C. saccharolyticus*	70°C Batch	44.68 mL H_2 g^{-1}dry biomass	-	[67]
Corn stalk	*C. butyricum*	36°C Batch	92.9 mL H_2 g^{-1} dry biomass	-	[68]
	Bacillus licheniformis	35 °C pH 6.0 (Pretreatment with 2% NaOH)	185 ml/l and 82.5 ml/g substrate	-	[69]
Rice straw	Waste water sludge	55°C Batch	24.8 mL H_2 g^{-1} dry biomass	-	[6]
Microalgae	Enriched functional consortia	30°C Batch	25.1 mL H g^{-1} dry biomass	-	[70]
L. japonica	Anaerobic	35°C Batch	71.4 mL H_2	-	[71]

	mixed culture		g^{-1} dry biomass		
Water hyacinth, beverage waste water	Pig slurry	$45^{\circ}C$ Batch	13.65 mL H_2 g^{-1}dry feedstock	-	[72]
Mixture of corn husk, hut shell, rice husk	Buffalo dung compost	$37^{\circ}C$ Batch	65.78 mL H_2 g^{-1}TVS	-	[73]
Waste papers	*R. albus*	$37^{\circ}C$ Batch	42.8–282.7 mL H_2 g^{-1}dry biomass	-	[74]
Switchgrass	*C. saccharolyticus*	$65^{\circ}C$ Batch	310 mL H_2 g^{-1} dry biomass	-	[75]
Deoiled Jatropha waste	Anaerobic mixed culture	$55^{\circ}C$ ASBR	8.7 mL H_2 g^{-1} VS	-	[76]
L. japonica	Anaerobic digester sludge	$35^{\circ}C$ ASBR	61.3 mL H_2 g^{-1} dry biomass	-	[77]

The studies listed above have two major limitations: firstly, they have produced feasibile results based on fixed type of substrate, specific reactor design and operational parameters, not for generic purposes; and secondly, the production processes were only conducted in laboratories. As a result, there was no dicussion regarding the production and relevant downstream processing challenges involved in large scale production.

3.2 Challenges in controlling process inhibition

Some process inhibition conditions can seriously compromise biohydrogen production during the anaerobic digestion process. The types of microorganism in biohydrogen production depend mainly on the type and composition of organic content in the substrate. The metabolic pathway for biohydrogen production is then defined by the microorganisms present in the system.Figure 1 summarizes several factors that work against biohydrogen production and make the process unfeasible for large scale industrial application.

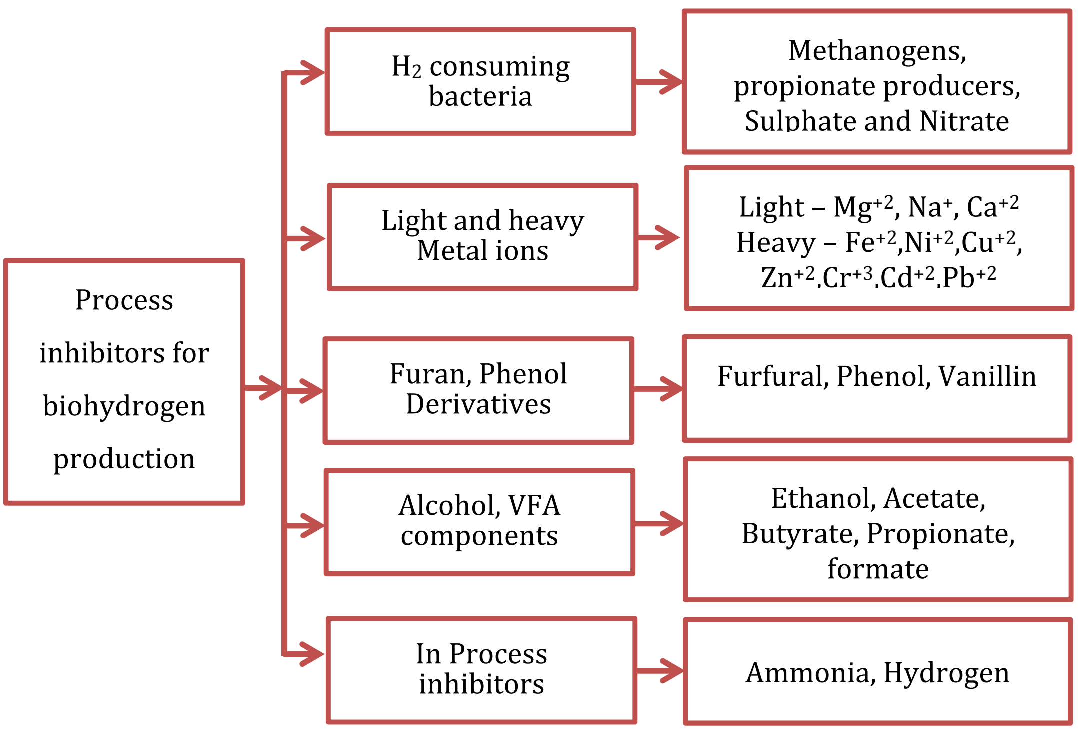

Figure 1: Inhibitors that discourage biohydrogen production

3.2.1 Hydrogen consuming bacteria

The final stage of anaerobic digestion involves the production of biomethane from the reduction of CO_2 using H_2 as the electron donor. The biohydrogen produced is consumed through the process known as hydrogenotrophic methanogenesis, which decreases the overall yield of biohydrogen [23]. Hydrogen is also consumed by the alcohol-producing bacteria, where it is consumed as an electron donor both in the form molecule or hydrogen equivalents ($NADH_2$; potential H_2). During dark fermentation, lactate is degraded by propionate producers such as Clostridium propionicum and Clostridium homopropionicum through the consumption of NADH [28, 29].

Sulfate reducing bacteria (SRB) use different types of substrate as the donor of electrons and cause the sulfates to be reduced to sulfides. SRBs perform their action simultaneously through partial oxidation (to acetic acid and CO_2) or complete oxidation (to CO_2 and HCO_3^-) [28]. Of the different types of SRB, hydrogenotrophic SRB constitute the major consumers of biohydrogen because they consume biohydrogen as an electron donor [78].

Another hydrogen consumer is Nitrate reducing bacteria (NRB) who can be either heterotrophic or autotrophic. Autotrophic NRBs utilize biohydrogen as electron donor to produce ammonia [20]. Besides, NRBs can also decrease biohydrogen production by producing ammonia; it has been proven through experiments that high concentrations of NH_3 and NH_4^+ have toxic and repressing effects in biohydrogen production through anaerobic process [79].

3.2.2 Light and heavy metal ions

Metals ions have been referred to as an important requirement for bacterial growth and enhanced enzyme and co-enzyme activity [80]. However, research studies have also revealed that a high concentration of metal ions can seriously discourage biohydrogen production [81]. Magnesium ion is referred to as a cellular protein builder and activator and cofactor for enzymes that help in the production of biohydrogen [80]. Yet, Bao et al. [82] suggested an inhibitory level of 20.0 mg/L Mg^{+2} supressed the biohydrogen production from starch. Similarly, Na^+ and Ca^{+2}

have also been reported as micronutrients that enhance bacterial growth and cell retention [83, 84]. Elsewhere, research studies have indicated that 2000 mg/L and 100 mg/L are the inhibitory thresholds for Na^{+} and Ca^{+2}, respectively [28, 85].

Iron has been identified as an important element to support bacterial growth, biosynthesis of enzymes and to reduce the sulphide inhibition for hydrogen production [82, 86]. But similar to sodium, magnesium and calcium ions, Fe^{+2} wields an inhibitory effect when the concentration reaches 100 mg/L [87]. Several other metal ions have also been reported as exerting inhibitory effects in biohydrogen production, for instance, 1600 mg/L for Ni^{+2} [88], 15, 3 and 0 mg/L for Cr, Cu, and Zn, respectively [89].

Bundhoo & Mohee [28] mentioned that dilution and precipitation as sulphides are two common methods used to control metal ion concentration below the threshold level. Additionally, adsorbents like activated carbons and organic ligands also could be utilized to control the heavy metal ion concentrations during the dark frermantation.

3.2.3 Furan, phenol derivatives from pre-treatment

Pre-treatment processes are applied to anaerobic digestion to break up the crystalline structure of cellulose and accelerate the rate of hydrolysis of the substrates [23, 90]. During the pre-treatment process toxic by-products such as phenolic compounds and furan derivatives are produced that have been identified to have inhibitory effect on biohydrogen production [28]. The major components of furan derivatives are referred to as furaldehyde (furfural) and hydroxymethylfurfural (HMF). Furan derivatives affect enzymic activities, cell membrane function, and glycolysis of fermentative bacteria during biohydrogen production [91]. Operating processes at high temperature and pressure trigger furfural production while the degradation of pentose encourages the production of HMF [28]. A threshhold range of 2-4 g/l concentration of furfural has been identified to decrease the production of biohydrogen from 29 – 63% [92].

Major phenolic components include vanillin and syringaldehyde during degradation of lignin or acid hydrolysis [93]. They have been reported to affect cell membranes by either by increasing their permeability or simply by damaging the membranes. As a result, the absence of protective barrier of the cell cytoplasm exposes the cell to extracellular toxic compounds [28, 93].

Production of furan and phenolic components cannot be avoided during pre-treatment, but their concentration could be lowered to reduce the inhibitory effect. In this connection, physical and chemical detoxification process may be performed by alkalination, washing and removal by subjecting the pre-hydrolysate to ion exchange resin [35], whereas biological detoxification involves treating the hydrolysate with enzymes or fungus [28].

3.2.4 Alcohol and VFA components

During the stage of acidogenesis in anaerobic digestion, volatile fatty acids (VFAs) and alcohols are being produced. The rate of initial hydrolysis and acidogenesis is higher compared to the final stage of methanogenesis where VFAs are consumed by the methanogens. As a result, the high concentration of accumulated VFA causes a sharp decrease in overall pH of the reactor [24, 94, 95]. The pH imbalance due to the production affects the growth of HPB and reduces the production of biohydrogen. Specifically, it has been asserted that ethanol does not suppress biohydrogen production compared to the VFA components [96].

Bundhoo & Mohee [28] explained the mechanism by which the volatile fatty acids perform their inhibition in biohydrogen production. During anaerobic digestion, fatty acids produced in the stage of acidogenesis may be present in either ionized or non-ionized forms. The ionized acid increase the ionic strength of the medium and eventually affects biohydrogen production as it shifts the metabolic pathway from acidogenesis to solventogenesis (where VFA is converted to organic solvents, namely butanol, acetone, and ethanol). The non-ionized acids penetrate to the cell membrane, dissociate due to the higher intracellular pH and finally, the H^+ concentration is increased. Cell death and suppression in biohydrogen production is caused by the pH imbalance caused from the influx of protons.

3.2.5 In process inhibitors

Ammonia, generated by either NRB or nitrogen-containing compounds is considered to be a source of nutrient for bacterial growth only to a certain extent, and high concentrations of NH_3 and NH_4^+ have been reported as proving toxic and inhibiting biohydrogen production [79, 97]. Ammonia passively diffuses into microbial cells and results abnormal cell ectoplasm, imbalance in sodium potassium exchange and finally changes the pH value, which affects the stability of the cell [98]. As a consequence, an imbalance in intercellular pH is observed and this results in reduced biohydrogen production [28].

A high concentration of produced biohydrogen in the liquid phase results in high partial pressure of hydrogen which causes biohydrogen production to decline [20]. During anaerobic digestion, the reduction of protons to hydrogen is thermodynamically favorable when the partial pressure of hydrogen is low. Continuous gas release, larger headspace volume, vacuum stripping or the gas spurging process could be applied to avoid this problem [28]. Subsequently, avoiding process inhibition conditions could be the basis for increasing the production of biohydrogen. Carbon content, type and composition of the feed material, operating conditions, and pretreatment processes define what particular process inhibition conditions need to be avoided during anaerobic hydrogen production.

3.3 Challenges in process optimization

Optimizing the anaerobic digestion for biohydrogen production could be classified into two major categories: for biohydrogen production only [99]; and for simultaneous production of biomethane and biohydrogen [23]. Some research studies have set out to establish the optimal values of common process parameters for biohydrogen production [24, 100]. The most common process parameters include temperature, pH, retention time (both HRT and SRT), organic loading rate and specific chemical additives that enhance the biohydrogen production. These parameters are explained in more detail below.

3.3.1 Temperature

So far, no research study has directly compared the relative biohydrogen production rate using different process temperatures. The work of Zhong et al. [21] mentions 131.5 ml H_2/g-$COD_{removed}$ at 60 °C compared to 116.5 ml H_2/g-$COD_{removed}$ at 40 °C. These findings could be explained from the assertion that high temperature makes a high rate of acclimatization and initial hydrolysis possible during anaerobic digestion [21, 101]. Results also documented that the activity of the enzymes was higher at a high temperature [21]. As mentioned previously, the products of initial hydrolysis (volatile fatty acids) act as precursors to hydrogen production in the next two stages. In this scenario, the high rate of hydrolysis favors hydrogen production.

For biohydrogen production, it is necessary to inhibit the activities of hydrogen consuming bacteria such as methanogens. Two common processes to inhibit methanogenic activity are heat and load shock treatment [24]. Jariyaboon et al. [101] has reported a temperature of 100 °C for sludge treatment (30 minutes) in a thermophilic two-stage anaerobic digestion processing skim latex serum.

In this context, the major challenge in selecting the best operating temperature is considering the trade-off between the cost associated in maintaining high temperature and the added amount of revenue for additional biohydrogen produced at that temperature. More research studies are needed to generalize the range of process operating temperatures in connection to the production rate and yield of biohydrogen.

3.3.2 pH

The metabolic pathway and growth rate of microorganisms are both defined by the pH of a reactor during biohydrogen production. Any change in hydrogen ion concentration results in a change in pH and eventually leads to a change in redox potential. These series of events can trigger a change in the rate of receiving electrons by the protons and finally the rate of biohydrogen production [102]. Unlike temperature, a certain pH range has proven to favor biohydrogen production. The pH 5.5-6.8 range has been reported to be ideal for biohydrogen production [103], whereas a value of 4.5 seems to have an inhibitory effect on biohydrogen production [102]. Same study recorded a pH of 5.5 ensured maximum biohydrogen production (1.47 mol H_2/mol hexose) from noodle manufacturing wastewater [102].

The high rate of hydrolysis enables faster production of volatile fatty acids in the initial stage. If the rates of acidogenesis and acetogenesis are slow compared to hydrolysis, then volatile fatty acids could accumulate in the bioreactor. The accumulation of VFA could result a sharp decrease in the overall pH of the reactor and eventually inhibit biohydrogen production [24]. Although the pH range is common for substrates with substrates with different values of organic content, maintaining the reactor pH can be a challenging option. In a laboratory scale study, controlling the pH of a reactor is relatively easy since the required amount of chemical additives is less compared to the demands of large scale production where more cost-effective methods are required to control the system's pH level.

3.3.3 Retention time

Regarding biohydrogen production, optimum values of hydraulic, solid retention time mainly depend on the bioreactor arrangement and type and composition of the substrate [12, 104, 105]. The aim of regulating HRT for a particular bioreactor should be to retain the hydrogen-producing bacteria while washing out the methane-producing bacteria. As a result, inhibition of homoacetogens, hydrogenotrophic methanogens, and prevention the washout of HPB both needs to be ensured [24].

The results of a recent study mentioned HRT values between 3 to 6 hours are suitable for maximum biohydrogen production rate (25.9 L H_2/L-d) from granular hydrogen-producing mixed cultures fed with galactose. In a thermophilic anaerobic co-digestion (80:20 mixtures from municipal solid waste and food waste), maximum daily yield of biohydrogen production was 2.51 L H_2/L reactor, at an SRT of 1.9 days [12]. Another experiment conducted by Kumar et al. [104] specified 6-18 h as the optimum HRT for the maximum biohydrogen production rate and yield (4.49 L/L/d and 1.62 mol/mol glucose, respectively).

In summary, longer SRT and shorter HRT have proven to be useful for the production of biohydrogen, but the specific process values would vary for different types of substrates.

Hence, determining the HRT and SRT values for an anaerobic system processing different types of substrates could be particularly challenging.

3.3.4 Organic Loading Rate

The organic content present in the substrate is later converted into molecular hydrogen during anaerobic digestion. As a result, for a specific bioreactor design, the organic loading rate needs to be optimized to ensure the maximum hydrogen production rate and yield. The initial increase in organic loading increases the production of biohydrogen. Shen et al. [106] performed an experiment to study fermentative hydrogen production at different loading rates (4.0, 6.0, 13, 22 and 30 g COD L^{-1} d^{-1}). The hydrogen production rate rose from 0.020 ± 0.004 to 0.196 ± 0.015 mol d^{-1} L^{-1} when the OLR increased from 4 to 22 g COD L^{-1} d^{-1}. Later a further increase to the OLR at 30 g COD L^{-1} d^{-1} reduced the production to 0.160 ± 0.003 mol d^{-1} L^{-1}. The maximum value of organic loading rate is dependent on the reactor type, arrangement, and type of organic substrate [24]. A novel bioreactor arrangement in this connection was utilized by [107] where an integrated biohydrogen reactor clarifier was coupled with CSTR. The results showed an optimum OLR of 103 gCOD/L-d for maximum hydrogen production of 2.8 mol /mol glucose.

Unfortunately, increasing the loading rate can cause problems like severe membrane fouling [106], reactor instability and inhibition of hydrogen production [107]. Results from the experiment conducted by Hafez et al. [107] also revealed that an optimum F/M ratio (4.4–6.4 gCOD/gVSS-d) should be maintained to ensure the maximum biohydrogen production without any deviation in the metabolic pathways or microbial shifts from biological hydrogen production. Finally, for given bioreactors type it needs to be optimized with a consideration that the maximum hydrogen production process must be stable.

3.3.5 The OLR-HRT relationship

The optimum value of OLR and HRT depend on each other for a given anaerobic process. Zhang et al. [105] carried out an experiment aiming to discover the effect of OLRs and HRTs on hydrogen production by halophilic hydrogen-producing bacterium (HHPB). One set of results included maximum 1.1 mol-H_2/mol-glucose at OLR of 20 g-glucose/L/day and HRT of 12 hours. Whereas increasing the OLR from 20 to 60 g-glucose/L-reactor/day at HRT 6 h, the hydrogen production rate increased for the same experiment.

Another experiment was carried out to study the effects on HRT and OLR in biohydrogen production based on lactate type fermentation [108]. The experiment was performed in OLRs: 10, 15, 20 and 40 g/L/day and hydraulic retention times were 6, 12 and 24 hours. The study concluded an OLR of 40 g/L/day and HRT of 12 days for maximum yield of continuous hydrogen production.

The experiment performed by Hafez et al. [107] included the application of six different organic loading rates (from 6.5 gCOD/L-d to 206 gCOD/L-d) with a gravity settler where solid retention time (SRT) was decoupled from the hydraulic retention time (HRT). At HRT 8 hours, 103 g COD/L-d was the optimum value of OLR for maximum hydrogen yield (2.8 mol H_2/mol glucose).

The trend concerning the hydrogen yield and production rate from this experiment suggests that the optimization approach should include one parameter that keeps the other condition constant. The best combination of values for both parameters should be identified for maximum biohydrogen production and yield.

3.3.6 Chemical additives of special treatment process

Different chemical additives have been proven to increase the efficiency of anaerobic digestion, specifically the generation of methane. So far, only a few studies have observed the effect of chemical additives on enhancing biohydrogen production derived from anaerobic digestion.

Apart from the conventional anaerobic system, heat pretreatment has been observed to enhance biohydrogen production. Results from one experiment included an increase from 14 ml H_2/gVS to 69.6 ml H_2/gVS when the inoculum was heat treated in a thermophilic scenario [109]. Additionally, metal additives like $FeSO_4$ can effectively increase the production of biohydrogen. Lee et al. [110] showed a H_2 production rate of 41.6 l/day using 10.9 mg $FeSO_4$/l H_2 which is 1.59 times higher compared to the production rate achieved at 2.7 mg $FeSO_4$/l.

A combination of pretreatment and adding chemicals in the first stage of anaerobic digestion has increased the level of biohydrogen production. Muñoz & Steinmetz [111] carried out a set of 21 set of experiments to observe the influence of pretreatment and chemical addition on biohydrogen production. Heat shock as microwave (5min @800W) was proven to be effective in that it produced a yield of 0.96 mol H_2/mol glucose compared to the yield of 0.62 mol H_2/mol glucose achieved by heat treatment at 90˚C using water bath. The same set of experiment used chemical additives like Bromoethanosulfonate (BES), Fe^{+3}, HCl and Chloroform ($CHCl_3$) for selective inhibition of methanogenesis. A yield of 0.52 mol H_2/mol glucose was achieved at BES concentration of 7mM but no environmental impact assessment is yet available for BES and its by-products.

Implementing any standalone or combination physical of chemical treatment process is dependent on two main criteria: Firstly, the cost-benefit analysis and energy balance should be performed when any pretreatment process is applied. The increase in revenue earned from biohydrogen should exceed the cost associated with the treatment process. Secondly, the environmental impact assessment should be performed for the selective methanogenic inhibitors and their potential by-products. The number of research studies, in this case, is limited, and any potential increase in biohydrogen production is still not well known. Challenges lie ahead to find the optimum combination of physical and chemical treatment process that would significantly increase the production of biohydrogen.

3.4 Challenges on hydrogen storage system

Developing a safe, reliable and economically feasible storage system for hydrogen is currently the biggest challenge for the widespread industrial application of hydrogen as a fuel. However, the envisaged storage system depends on the type of application. Gravimetric density is the dominating factor for automobile applications since volume of storage is limited, and a feasible driving range is expected [112]. For hydrogen transportation, process safety and high density of hydrogen are the predominant conditions for hydrogen storage. Figure 2 summarizes the basic categories of hydrogen storage system and their corresponding issues and applications.

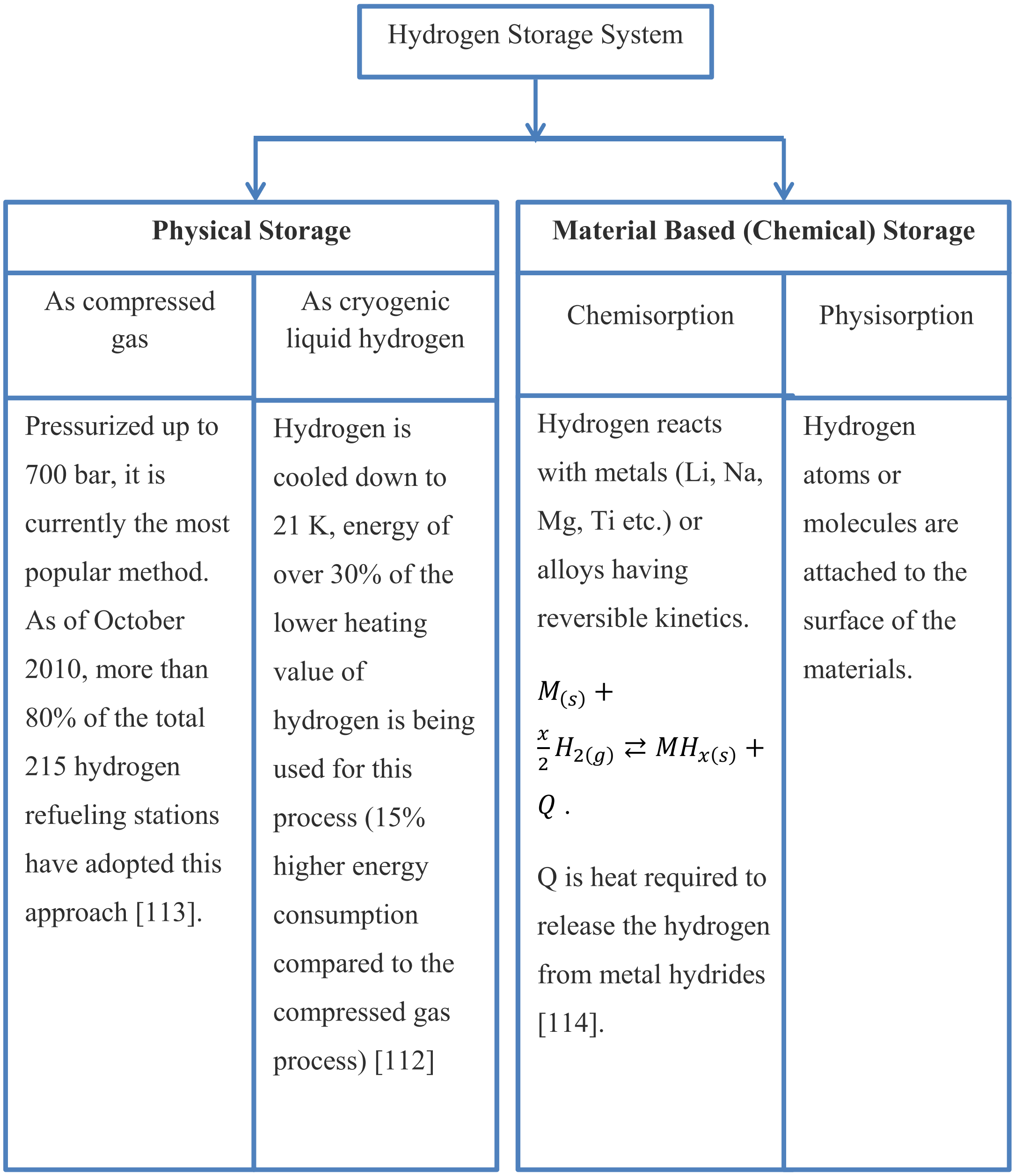

Figure 2: Basic categories of hydrogen production system

The common hydrogen storage techniques mentioned suffer from some technical difficulties. These disadvantages are as follows:

i) Low storage density is the main physical storage problem for hydrogen as compressed gas. According to Zhang et al. [112], the gravimetric densities of hydrogen are 5.5 and 4.6 wt. % at 350 and 700 bars, respectively. This outcome implies the compressed storage system of hydrogen as gas is not feasible for automobiles [112, 115]. Challenges lie ahead to identify a suitable material that can meet the targets of volumetric capacity in addition to stress and safety for high pressure storage tanks.

ii) Low pressure liquid hydrogen storage system has advatntages including high fuel density and low cost compared to the pressurized storage as compressed gas but has a technial limitation due the evaporative loss of hydrogen [4]. Additionally, the expensiveness of high energy consumption during the liquefaction process is a major hurdle for this process [112].

iii) Boiling-off for liquid hydrogen storage is another problem where the system can lose up to 2-3% hydrogen in a single day [112]. This scenario not only contributes to the fueling frequency and cost but also poses a potential threat to safety when the storage system is located in a confined space.

iv) Hydrogen embrittlement is a general issue for hydrogen storage where materials in continuous contact with hydrogen become brittle. Lone hydrogen atoms are diffused into the metal structure, and the recombined hydrogen molecules atoms create pressure from the cavity and initiate a crack in the metal [1]. The single metal or alloy with the ability to avoid embrittlement is yet to be identified.

v) Pure metal hydrides have individual drawbacks in the hydrogen storage system, for instance: NaH and CaH_2 have good reversible kinetics but low wt. % (4.2 and 4.8, respectively) of hydrogen, MgH_2 and LiH has poor reversibility, and AlH_3 production demands high pressure [116]. As a result, recent research focus is more inclined to finding the best composition for a metal alloy that makes hydride production possible, and reversible reaction kinetics can be applied for hydrogen recovery.

vi) The most recent research approaches include the formation of multi-cation borohydrides $MM'(BH_4)_n$ including $ZrLi(BH_4)_5$, $ZrLi_2(BH_4)_6$, $LiK(BH_4)_2$, $LiSc(BH_4)_4$

[112, 117] and amides $M(NH_2)x$ due to their high storage capacity and low operating temperature [112]. However, their application is limited due to poor absorption capacity and costs involved in adsorption/desorption [118].

Apart from the technical challenges that are evident in hydrogen storage, cost and practicality have not made widespread industrial application feasible. The following table includes the current and projected target for H_2 storage systems.

Table 4: Target and current status of H_2 storage technologies [119]

Storage targets	**Gravimetric kWh/kg(kgH₂/kg system)**	**Volumetric kWh/L(kgH₂/L system)**	**Costs$/kWh($/kgH₂)**
2017	1.8 (0.055)	1.3 (0.040)	$12 ($400)
Ultimate	205 (0.075)	2.3 (0.070)	$8 ($266)
Projected H_2 storage system performance	**Gravimetric (kWh/kg)**	**Volumetric (kWh/L)**	**Costs ($/kWh)**
700 bar compressed (Type IV)	1.5	0.8	17
350 bar compressed (Type IV)	1.8	0.6	13
Metal hydride (NaAlH4)	0.4	0.4	TBD
Sorbent (MOF-5, 100 bar)	1.1	0.7	16
Chemical hydrogen storage (AB-50 wt. %)	1.7	1.3	16

4. Potential of biohydrogen as renewable energy

4.1 Predicting the availability of fossil fuels in the future

The current usage of fossil fuel is approximately 89 million barrels per day according to the statistics published by the International Energy Agency (IEA) [1]. The Intergovernmental Panel on Climate Change (IPCC) has reported that 275 GtC of fossil fuels could be produced from the total reserve of 746 GtC for the remainder of this century only if the anthropogenic climate change is controlled to ≤2 °C [120]. However, it is particularly difficult to project the demand for fossil fuels in the future since the level of demand is dependent on fuel cost and supply. Asafu et al. [121] carried out a pooled mean group analysis to predict economic growth and fossil and non-fossil fuel consumption. They concluded an annual worldwide growth rate of 2.41% and 3.62% for annual fossil fuel and non-fossil fuel energy sources, respectively.

The availability of fossil fuels in the future is subjected to three major uncertainties: technical, economic and political situations [122]. Technical advances like hydraulic fracturing (fracking), deep water seismic survey, long-wall mining, etc., have increased the amount of fossil fuel obtained from reservoirs. Conversely, the cost involved in these advanced technologies should be considered too. Research studies have shown that the cost can increase from 7.65 to 15.2 million USD when the oil well depth changes from 2400 to 4600 meters [123]. Furthermore, recovering oil and gas from hydraulic cracking has negative environmental and economic factors such as water and air pollution, use of additional infrastructure and high water consumption (6 million gallons of pressurized water with chemicals) [124]. Under these circumstances, technological advances are not always sustainable regarding cost and the long term impact on the environment.

As a result, relying on the fossil fuel reserve is not the best possible option when considering energy sustainability over the long term. In 2012, fossil fuel contributed to 68% of the total electricity generated worldwide. On the other hand, the overall renewable energy production was 4862 TWh [125]. By 2018 it is predicted that overall renewable energy will reach 6851 TWh [125]. It can be stated here that the gradual depletion of fossil fuel resources, expensive recovery and exponential growth in demand poses a serious threat to the sustainability of energy supplies. Biohydrogen production could be the key to achieving sustainable sources of renewable energy in the future.

4.2 Energy density and fuel properties

Compared to conventional fossil fuel energy sources, hydrogen is considered to be an important alternative because of its high energy density. The average energy density of hydrogen per mass content is equal to 143 MJ kg^{-1}, which is about three times more compared to the energy densities of fossil fuels [1]. It has been reported that 10% blend of hydrogen with natural gas in internal combustion engines can reduce up to 95% greenhouse gas emissions [18]. Table 5 compares the energy densities of some common fuels.

Table 5: Energy density of some common fuels (Modified from [1, 126]).

Fuel	**Process conditions**	**Energy per kilogram (MJ kg^{-1})**
Hydrogen (liquid)	Liquid	143
Hydrogen (compressed, 700 bar)	Compressed at 700 bar	143
Hydrogen (ambient pressure)	Ambient pressure	143
Methane (ambient pressure)	Ambient pressure	55.6

Fuel	**Process conditions**	**Energy per kilogram (MJ kg^{-1})**
Natural gas (liquid)	Liquid	53.6
Natural gas (compressed, 250 bar)	Compressed at 250 bar	53.6
Natural gas	-	53.6
Liquefied natural gas (LNG)		19.9
Compressed natural gas (CNG)		19.9
LPG propane	-	49.6
LPG butane	-	49.1
Gasoline (petrol)	-	46.4
Biodiesel oil	-	42.2
Diesel	-	45.4
Methanol		22.7
Ethanol		29.7

Considering an alternative source of energy, hydrogen has a great advantage over other renewable sources. Methanol or ethanol has an energy density of 19.98 which is significantly less than hydrogen. Also, the flash points of methanol and ethanol are 11 and 13 °C, respectively, and this means the alcohol storage tank would have a flammable atmosphere even at an ambient temperature. Table 6 below presents an additional list of the properties of hydrogen and some other common fuels that are important to evaluate their potential as fuel.

Table 6: Comparison of common fuel properties between gasoline, methane, and hydrogen (modified from [126, 127]).

Property	**Gasoline**	**Methane**	**Hydrogen**

Minimum ignition energy (mJ)	0.2	0.2	0.017
Diffusion coefficient in air (cm^2/s)	0.05	0.16	0.610
Specific heat at constant pressure (J/kg K)	1.20	2.22	14.89
Flammable limit in air (vol%)	1.0–7.6	5.3–15.0	4.0–75.0
Flammable energy in air (MJ)	0.24	0.29	0.02
Flammable temperature (K)	501–744	813	858
Flame temperature in air (K)	2470	2148	2318
Explosion limit in air (vol%)	1.1–3.3	6.3–14.0	13.0–59.0

In addition to the energy density, two other properties of hydrogen have made this more sensitive to ignition. Firstly, the minimum ignition energy (minimum energy required to ignite an optimum air-fuel mixture) for hydrogen has been recorded as 0.017 mJ compared to the value of 0.2 mJ for hydrocarbons [126]. Secondly, the flammable limit for hydrogen is 4-75 % (v/v) compared to the value of 1.4–7.4 % (v/v) for gasoline which explains why hydrogen could detonate readily compared to hydrocarbons [126].

4.3 Effect on the environment

Conservation of the environment and sustainability are now the most prioritized section in aspects of any fossil fuel's evaluation. The primary product from the combustion of fossil fuels is CO_2 and CO where additional impurities' supply of air also leads to the production of NO_X and oxides of sulfur [127]. In contrast, the only possible product from the combustion of hydrogen is water vapor which has no significant direct effect on the environment or human health. The statistics related to the emission of pollutants, such as SO_x, NOx, carbon monoxide and carbon dioxide emphasize the superiority of hydrogen over fossil fuels. To provide an idea of the effects of air pollution, Figure 3 lists the common industrial pollutants that are now typical in industrialized countries.

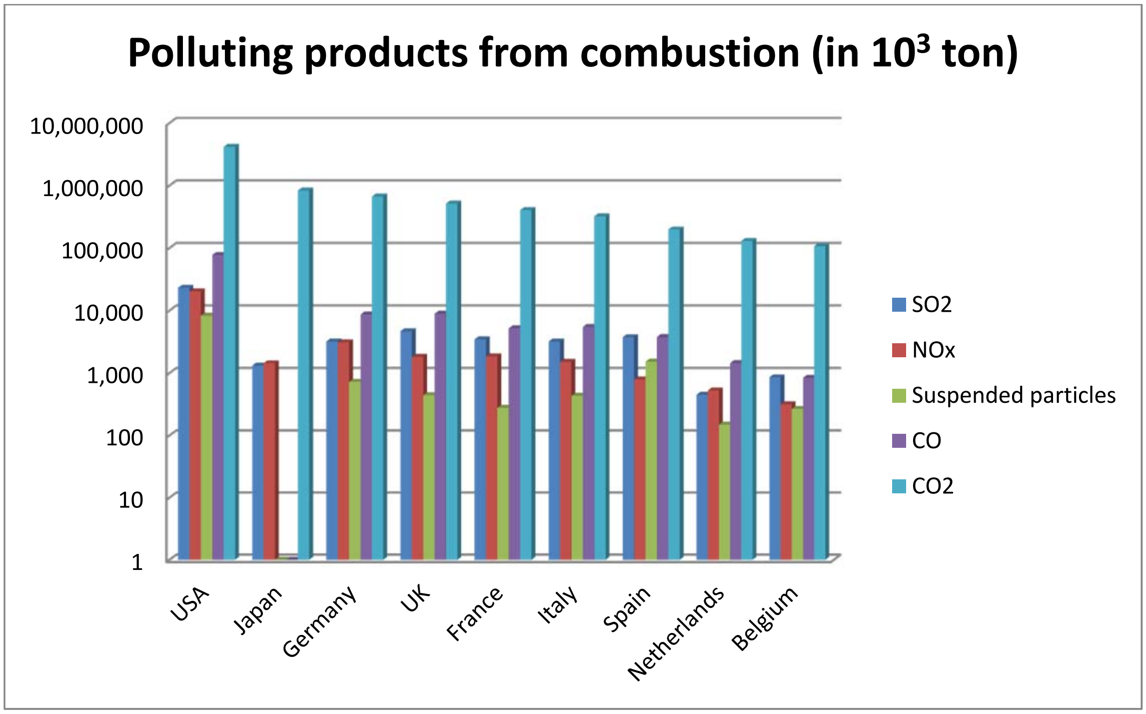

Figure 3: Comparison between the main pollution emissions in the industrialized countries (Data adapted from [127]).

Nicoletti et al. [127] compared the weighted percentages of pollutants in combustion flue gas concerning hydrogen, carbon, methane and octane. From the results listed in Table 7, it is clearly evident that the combustion of hydrogen offers zero emissions regarding CO_2 and SO_2 apart from the emission of nitrogen oxides. The formation of NO_x is a function of flame temperature and duration [128]. Considering the broad flammability range of hydrogen, its combustion can be influenced how an engine has been designed, so the aim should be to reduce NO_x emissions.

Table 7: Weighted percentages of pollutants in combustion flue gas for common fuels

Fuel	**kg Pollutants /kg of fuel**				
	CO_2	**SO_2**	**NO_x**	**Un-burnts, particulates**	**H_2O**
H_2	0	0	0.016	0	7
C	1.893	0.012	0.008	0.1	0.633
CH_4	2.75	0.03	0.0075	0	2.154
C_8H_{18}	3.09	0.010	0.0115	0.85	1.254

The table does not include pollutants like Volatile Organic Materials (VOCs), radioactive materials and heavy metals that may be present with fossil fuels during combustion. Impacts on the environment that are additional to greenhouse gas emissions have been mentioned by Khan et al. [23]. For example, methane containing biogas is produced by the process of anaerobic digestion. Besides combustion, methane could be present in the liquid effluent that leads to environmental problems like eutrophication, marine aquatic eco-toxicity, freshwater aquatic eco-toxicity, terrestrial eco-toxicity, human toxicity, etc. Since hydrogen is not soluble in water, the production of hydrogen from anaerobic digestion could eliminate these serious environmental problems.

The advantage of hydrogen as a clean energy source is evident in that it reduces the release of pollutants into the environment. To limit the rise of global average temperature < 2°C, maximum allowable emission limit carbon dioxide should be around 565-886 billion tones until 2050 [129]. Achieving this target would only be possible if more emphasis is given on developing and employing alternative energy sources like hydrogen.

4.4 Estimating cost of hydrogen compared to conventional energy sources

A typical cost analysis model includes the energy supply system (production cost, production level, available resources, etc.), energy markets (fuel prices, price adjustment), consumer choice behavior (consumer utility, fuel demand, vehicle adoption) and refueling infrastructure [130]. The following discussion will focus on the production and storage cost of hydrogen as fuel.

Hydrogen production on an industrial scale is not considered to be an economically feasible option. The sustainability of hydrogen production has been criticized because the production process from carbon sources requires fossil fuels as raw materials and external costs are associated with carbon capture and storage. Furthermore, production of hydrogen from anaerobic digestion is also variable as different anaerobic process contains substrates containing different carbon composition. Some cost comparisons have been done regarding different hydrogen production processes [131], but it has been particularly challenging to compare hydrogen production costs to continuously changing fuel and oil prices. Table 8 contains the summary of overall hydrogen production cost from different raw materials and processes.

Table 8: Cost of hydrogen production using different energy sources

Raw material	**Process**	**Production cost ($\$/kgH_2$)**	**References**
Natural gas	Steam Methane Reforming	0.75	[132]
Natural gas	Steam Methane Reforming (with carbon capture & storage)	2.67	[133]
Nuclear	Electrolysis	2.4	

Nuclear	High Temperature Electrolysis	3.5	[134]
Nuclear	Copper–chlorine	1.7	[135]
Nuclear	Sulfur–iodine cycle	1.9	
Coal	Gasification (with carbon capture & storage)	1.8	
Solar	Electrolysis	7.7	[136]
Solar	Photovoltaic electrolysis	9.1	[137]
Solar	Photoelectrochemical	3.5	[138]
Wind	Electrolysis	7.2	[135]
Wind	Electrolysis	7.3	[139]
Biomass	Gasification	1.65	[140]
Biomass	Gasification	1.4–2	[141]
Biomass	Pyrolysis	1.3–2.2	
Biomass	Gasification	4.60–7.86	[142]
Geothermal	Steam electrolysis	1–2.6	[143]

From Table 8, it is evident that the lowest production cost for steam methane reforming process is 0.75 USD per kg of hydrogen whereas the maximum retail price of gasoline was 3.5 USD per gallon considering the time from 1994 to 2011. However, the costs associated with carbon capture and storage from CO_2 produced from gasoline has not been accounted for in this calculation. Additionally, it is expected that by the year 2030 the supply/demand gap in global oil and gas production will increase when demand for energy will rise by 60% [131]. It will, therefore, be predicted that oil and gas prices will rise over time in the next few decades.

The costs involved in carbon capture and storage are variable since the type of carbon capture, and storage process differ, and the expenses required for building the infrastructure for CCS also vary. The US National Energy Technology Laboratory has estimated USD 16/t CO_2 for carbon capture and storage [144]. Given the current trend of fossil fuel usage, global CO_2 emissions could rise to 44 billion tones by 2040 [145], and it means that approximately $704 billion USD will have to be spent on capture and storage technologies and processes. Such costs can only be reduced if the increased demand for energy is satisfied by the production of biohydrogen from renewable energy sources.

An average of 50 million metric tons of hydrogen is produced worldwide annually where 76–77% of the produced hydrogen is converted from natural gas and oil (Naphtha), 19–20% is produced from coal, and the remaining 3–4% is produced from renewable sources [131]. As the majority of hydrogen production involves the usage of fossil fuel as raw materials, production costs have not been competitive enough compared to the traditional energy sources such as gasoline or petrol. For example, Lee [146] performed cost benefit analysis and evaluation of financial feasibility of full commercialization of biohydrogen. The study was performed on cost-capacity scaling methods for different biohydrogen production plants. Their final results showed 2.20, 3.37, and 3.85 benefit/cost ratios for three different scenarios respectively. Additionally, Internal Rate of Return (IRR) and External Rate of Return (ERR) were calculated to 42.45%, 58.71%, 62.77%, and 14.40%, 16.05%, and 16.53% in payback periods of 11.33, 8.95 and 8.52 years.

Another study involved the cost benefit analysis of carbon footprint from hydrogen fueled scooter and Internal Combustion Engine (ICE) scooters [147]. The experiment came up with a result that the hydrogen fueled scooter from Steam Methane Reforming (SMR) process has the smallest carbon emission (0.0115 kg CO_2). As a result, the cost involved in carbon capture and storage would be less compared to the biohydrogen production process [148]. Same study measured the total life cycle and came up with a result that the total life cycle cost (excluding fixed costs i.e. cost of the vehicle, hydrogen production unit, etc.) is maximum (USD 6632) for the hydrogen fueled scooter whereas the ICE scooters have an amount of USD 4233. However, the reason was quite obvious as the hydrogen fueled scooter was using the SMR process. As a result, hydrogen fuel generation from biomass could be an interesting research option to reduce the total life cycle costs for hydrogen fueled vehicles.

On the other hand, some cost benefit analysis has produced negative results leaving the concept of hydrogen fueled vehicles not being a feasible option. Ito & Managi [149] investigated the economic validity of diffusion of hydrogen Fuel Cell Vehicles (FCV) and all Electric Vehicle (EV) in Japan. The differences between net present value between benefit and cost were studied to find out the economically feasible option between these two. The highest net positive value (NPV) was – 19 billion dollar based on 5 million FCV vehicle diffusion scenarios. However, the major limitation of this study lies in the calculation of total cost estimation. The authors estimated the differences in vehicle purchase and operating costs for FCV and Internal Combustion Vehicles (ICV) and added the differences to find out the total cost. Surely, the actual cost was not reflected during the cost benefit analysis of this study.

Regarding energy storage and transport, hydrogen fuel could be considered as an economically favorable option for term storage. A study compared the cost comparison of pumped-hydro, hydrogen storage and compressed air energy [150]. This calculation included the average discounted electricity generation cost, termed as “Levelized Electricity cost”

(LEC) for three different energy sources. For a long term storage scenario, the findings included a reduction of 70% LEC for hydrogen storage compared to 10% and 20% reductions for pumped hydro and compressed air storage, respectively. This research study suggested that by 2030 hydrogen storage would emerge as the best source of energy for all storage-discharge paths.

In a summary, the available cost benefit analyses for hydrogen fuel have been subjected to specific usage conditions, but the major limitation is the exclusion of carbon capture and storage cost when fossil fuels are used for hydrogen generation. Therefore, cost benefit analysis for biohydrogen production could be a future scope of research for improved economic feasibility.

5. Conclusion

The potential of biohydrogen regarding energy efficiency, environmental impact and cost-effectiveness has been described in detail in this paper. It is evident that biohydrogen is one of the best – if not the best - alternatives to fossil fuel energy. Biohydrogen production also offers an added advantage of not posing a threat to the environment during production, and there are zero external costs for carbon capture and storage. Unfortunately, proposed large scale industrial production has been hindered by some important technical and economic challenges. The knowledge garnered from existing research studies could be utilized to design a generic production model that makes the production of biohydrogen profitable and sustainable.

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