



HAL
open science

Reviewing the potential of bio-hydrogen production by fermentation

Jan Baeyens, Huili Zhang, Jiapei Nie, Lise Appels, Raf Dewil, Renaud Ansart,
Yimin Deng

► **To cite this version:**

Jan Baeyens, Huili Zhang, Jiapei Nie, Lise Appels, Raf Dewil, et al.. Reviewing the potential of bio-hydrogen production by fermentation. *Renewable and Sustainable Energy Reviews*, 2020, 131, pp.0. 10.1016/j.rser.2020.110023 . hal-02944546

HAL Id: hal-02944546

<https://hal.science/hal-02944546v1>

Submitted on 21 Sep 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Open Archive Toulouse Archive Ouverte

OATAO is an open access repository that collects the work of Toulouse researchers and makes it freely available over the web where possible

This is an author's version published in: <https://oatao.univ-toulouse.fr/26526>

Official URL :

<https://doi.org/10.1016/j.rser.2020.110023>

To cite this version:

Baeyens, Jan and Zhang, Huili and Nie, Jiapei and Appels, Lise and Dewil, Raf and Ansart, Renaud and Deng, Yimin *Reviewing the potential of bio-hydrogen production by fermentation*. (2020) *Renewable and Sustainable Energy Reviews*, 131. ISSN 1364-0321

Any correspondence concerning this service should be sent to the repository administrator: tech-oatao@listes-diff.inp-toulouse.fr

Reviewing the potential of bio-hydrogen production by fermentation

Jan Baeyens^a, Huili Zhang^b, Jiapei Nie^b, Lise Appels^c, Raf Dewil^c, Renaud Ansart^d, Yimin Deng^{a,c,*}

^a BUCT, Beijing Advanced Innovation Centre of Soft Matter Science and Engineering, Beijing Chaoyang District, 100029, China

^b Beijing University of Chemical Technology (BUCT), School of Life Science and Technology, Beijing, Chaoyang District, 100029, China

^c KU Leuven, Department of Chemical Engineering, Process and Environmental Technology Lab, J. De Nayerlaan 5, 2860, Sint-Katelijne-Waver, Belgium

^d Laboratoire de Génie Chimique, Université de Toulouse, CNRS, INPT, UPS, Toulouse, France

ARTICLE INFO

Keywords:

Hydrogen
Production
Biochemical
Pathways
Fermentation
Volatile fatty acids
Hydrogen recovery

ABSTRACT

Hydrogen is a common reactant in the petro-chemical industry and moreover recognized as a potential fuel within the next 20 years. The production of hydrogen from biomass and carbohydrate feedstock, though undoubtedly desirable and favored, is still at the level of laboratory or pilot scale. The present work reviews the current researched pathways. Different types of carbohydrates, and waste biomass are identified as feedstock for the fermentative bio-hydrogen production. Although all techniques suffer from drawbacks of a low H₂ yield and the production of a liquid waste stream rich in VFAs that needs further treatment, the technical advances foster the commercial utilization. Bacterial strains capable of high hydrogen yield are assessed, together with advanced techniques of co-culture fermentation and metabolic engineering. Residual VFAs can be converted. The review provides an insight on how fermentation can be conducted for a wide spectrum of feedstock and how fermentation effluent can be valorized by integrating fermentation with other systems, leading to an improved industrial potential of the technique. To boost the fermentation potential, additional research should firstly target its demonstration on pilot or industrial scale to prove the process efficiency, production costs and method reliability. It should secondly focus on optimizing the micro-organism functionality, and should finally develop and demonstrate a viable valorization of the residual VFA-rich waste streams.

1. Hydrogen and traditional production methods

Hydrogen is a common reactant in the petro-chemical industry and recognized as a potential fuel within the next 20 years. IHS Chemical expects an annual worldwide increase of the demand for hydrogen by nearly 4–5% during the next five years. Asia continues to dominate the increased demand due to the progressive growth of its domestic economies [1]. The major applications of hydrogen are at present in processing fossil fuels and in synthesizing ammonia. Hydrogen also serves as a reactant in the production of methanol. Minor applications include the hydrogenation of fats, fuel cells and the demonstration in hydrogen-fuelled vehicles. The worldwide distribution of the consumption of hydrogen is summarized in Fig. 1.

With depleting fossil fuels, bio-hydrogen is increasingly considered as a potential renewable and top energy source for its clean combustion and its high specific energy, i.e. 123 MJ/kg or ~3 times higher than petro-based fuels (~46 MJ/kg). The enhanced demand of hydrogen has been significantly influenced by its use in the desulfurization of

transportation fuel, and by the growth of the transportation sector [2]. Co-currently the quality of crudes is diminishing, leading to a decrease of hydrogen generation from crude processing. This has caused refineries to re-evaluate the hydrogen availability. Numerous research is being conducted on appropriate hydrogen production [3–7], storage [7–12] and application [5,6]. Though hydrogen is proposed as an alternative for fossil fuels, this application is however depending on the availability of technologies to enable a sustainable production of hydrogen, most of which are still under development. Bio-hydrogen could soon be entering the fuel market, provided the cost of the pre-cited steps decreases considerably [5,13]. Under this circumstance, worldwide ongoing research on hydrogen generation and storage is intensive.

Hydrogen can be prepared through various methods. Refineries, as mentioned above, are large-volume consumers of hydrogen as well as producers. Till now, fossil fuels are the main feedstock of 96% of all hydrogen: natural gas accounts for ~49%, liquid hydrocarbons are involved for ~29% and coal represents ~18% of the hydrogen production. Electrolysis (3.9%) and other by-product sources of hydrogen

* Corresponding author.

E-mail address: yimin.deng@student.kuleuven.be (Y. Deng).

Abbreviations

ADP	adenosine diphosphate
ATP	adenosine triphosphate
B	batch operating mode
C	continuous operating mode
<i>fhl</i>	formate hydrogen lyase complex
<i>ldhA</i>	lactate dehydrogenase
ORP	oxidation-reduction potential
PEM	polymer electrolyte membrane
PFL	pyruvate formate-lyase
PFOR	pyruvate ferredoxin oxidoreductase
PHB	poly- β -hydroxybutyrate
PNS	purple non-sulphur
VFA	volatile fatty acid

Symbols

BOD, COD	biological and chemical oxygen demand, respectively, g/L
HHV	high heating value, MJ/Nm ³
T	temperature, K

(0.1%) make up the remaining 4% [4–6].

Steam reforming of methane from natural gas or syngas is now economically the most important process of industrial bulk hydrogen production, and also involves removal of hydrogen from hydrocarbons [14]. At high temperature, i.e. 700–1100 °C, steam (water vapor) and methane react to form hydrogen and carbon monoxide:



The CO produced can further react with steam to yields extra H₂ through the water-gas-shift (WGS) reaction:



Electrolysis of water is responsible for about 3.9% of the worldwide hydrogen production [6], and is normally used onsite:



Most industrial electrolysis cells apply complex platinum electrodes

(plates or honeycombs). Generally, electrolysis as a hydrogen production method is only used for specific applications such as oxy-hydrogen torches or when extremely high purity hydrogen is required.

Innovations such as the application of Polymer Electrolyte Membrane (PEM) electrolysis [15] and microbial reverse-electrodialysis electrolysis cells [16] are currently under investigation. New configurations of a typical water electrolysis system are evaluated. The efficiency of a water electrolysis hydrogen production system under different operating conditions was calculated in detail by Zhang et al. [17], which can be helpful for further understanding and developing water electrolysis systems for H₂ production.

Although bio-hydrogen produced from renewable sources could be a promising production method, its contribution is below 1% so far.

Large industrial-scale hydrogen production from biomass or carbohydrates, i.e. hydrogen by fermentation, is undoubtedly desirable and favored, however still at the level of laboratory or pilot scale, as assessed in section 2 below. Strategies for industrial-scale production need to be developed, and further research is still needed.

Since hydrogen yields are reported to be low, it is important to select feedstock that is cheap, rather than using carbohydrate-rich raw materials such as starch, corn or sugars, of high commercial value and contributing to the human food-requirements. Waste biomass streams, with lower but accessible concentrations of carbohydrates, and offered at a limited or at zero cost (since needing to be treated prior to discharge) are economically the selected feedstock for bio-hydrogen production. It is therefore important to compare the different feedstock towards their real hydrogen production potential.

The hydrogen production by fermentation generally refers to three main categories, i.e. firstly by dark-fermentation, where no light is involved; secondly by photo-fermentation with light as the source of energy; and thirdly by combining photo- and dark-fermentation.

It should also be mentioned that the production of hydrogen by biomass gasification is often considered within the bio-production scope. The gasification technique is however of thermo-chemical nature, and hence not within the category of biochemical production methods. Gasification is well-documented in literature for both laboratory, pilot and industrial scale, with numerous review and research papers available. Gasification is therefore not considered in the present biochemical production review.

2. The bio-production of hydrogen through fermentation

In dealing with the fermentation production of H₂, several aspects

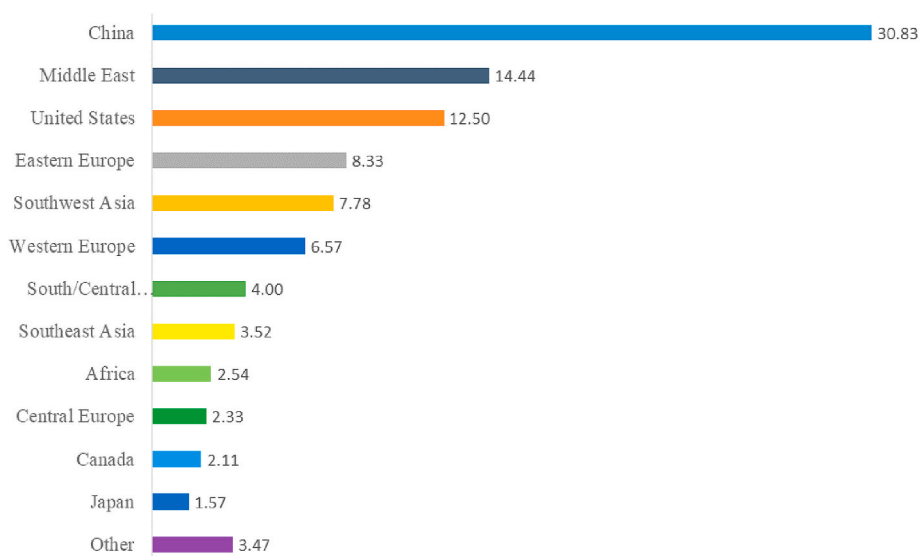


Fig. 1. Geographic distribution (%) of the worldwide hydrogen consumption.

should be considered to understand the selected feedstock and the principles of the principal technologies used, i.e. dark and photo fermentation, and their combined 2-step application. These aspects are dealt with below.

2.1. Carbohydrate substrates utilized for bio-hydrogen production

According to the fermentation principles, the use of carbohydrates offers the highest potential. Carbohydrates such as glucose, sucrose and starch were initially investigated, despite their high cost (300–1000 €/ton), hence hampering large-scale production and competing with the food cycle.

There are however numerous waste products that contain a wide range of carbohydrates [18] and are available at very low cost, since otherwise to be treated to meet environmental standards [19,20]. These waste feedstock streams can be of industrial, agricultural, municipal or forestry origin.

For most of these waste feedstock materials, pretreatments are necessary to liberate e.g. glucose by saccharification of the macromolecules. It should however be remembered that the pretreatment processes can generate inhibitors unless the pretreatment method is carefully selected, as illustrated in Table 1, where these substrates and there required pretreatments are summarized.

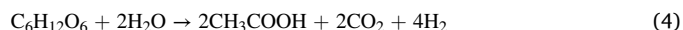
For cellulosic substrates, various chemical, biological and enzymatic pretreatments are possible [21–24]. These pretreatments can disrupt the stable structure of cellulosic materials, resulting in a higher surface area and an increased hydrolysis rate of cellulose materials. They can also decrease the degree of crystallinity and of cellulose/hemicelluloses polymerization [25]. Besides pretreatment, other measures can also be taken to increase the bio-hydrogen yield of cellulose substrates, including manipulation of carbon and electron flows through a metabolic shift caused by end-product inhibition, metabolic engineering at the genetic level, fermentation by co-cultures, and appropriate reactor designs [26,27].

Recently, also algae have been considered as potential feedstock, due to their content of polysaccharides and carbohydrates, e.g. between 8

and 30 wt% in microalgae and a lower wt% in macro-algae [46]. Further research is however required before the H₂ yield can be validated and economically assessed.

2.2. Dark fermentation

Dark fermentative avoids the problem of needing light as the necessary energy resource. The production proceeds mostly through the acetate and butyrate pathways [47].



Most literature sources investigate the microorganism species of the *Clostridium* genus because of their high hydrogen production rates. In addition, these bacteria possess ideal properties for industrial application, including forming endospores and high growth rates [47]. *Clostridium* sp. also allows mixed culture hydrogen production, in which the variety of species present facilitates the efficient decomposition and conversion of organic waste into hydrogen. The conversion process is generally accompanied by organic acid production [47].

The fermentative hydrogen production process is self-inhibiting once the partial pressure of hydrogen exceeds a critical value, which induces a switch to a different metabolic pathway in which acetyl-CoA and CO₂ are produced instead of hydrogen and organic acids [48] (Fig. 2).

Different bacterial strains have been used in the dark fermentation of various carbohydrate feedstock. Productivities are generally expressed in the molar amount of H₂ produced per mol of substrate. Results are depicted in Fig. 3. With molecular weights of 180 g for glucose and galactose, 342 g for sucrose and lactose, and 2 g/mol for H₂, the production yields can be converted into g H₂/g substrate. Waste water treatment sludge was also used as substrate for DF by *Chlostridium bifermentans* and *Pseudomonas* sp. GZI, however with low H₂ yields (0.9 mmol/g dried sludge, or about 0.1 mol/mol dried sludge, if the molecular formula of activated sludge is approximated as C₅H₇O₂N) [50,51].

Other commonly used enteric bacteria, such as *Escherichia coli* and

Table 1
Waste substrates utilized for fermentation bio-hydrogen production.

Waste sources	Substrates	Pretreatment	pH	Inhibitors	Hydrogen yield
Industrial	Paper solid waste [28]	Crushed to < 0.5 mm	2.5% H ₂ SO ₄	–	61.1 mmol/h/g
	Waste peach pulp [29]	Boiled for 45 min	–	–	123.27 mL/g TOC
	Wastewater from citrus processing [30]	suspended	–	–	85.4 mmol/L
	Vinasse from citrus processing [30]	solids and settled inorganics removed	–	–	13.4 mmol/L
	Vinegar residue [25]	heat (99 °C for 30 min)	1(10 mL HCl/g)	NH ⁴ -N, acetate, butyrate	53.2 mL/g VS
	Waste activated sludge [31]	γ-irradiation	12.0	Low pH	1.07 mL/L sludge
	Sewage sludge [32]	Heat treatment (150 °C for 30 min) with alkaline condition	–	Ammonia	39.0–220.3 mL/L sludge
Agricultural	Cassava starch wastewater [33,34]	Without treatment	–	–	287 mL/g starch, 0.3 mol H ₂ /mol
	Dairy cow solid waste [35]	Dried and crushed; hydrolyzed the dilute acid	–	VFAs and alcohols	97 mL/g
	Cassava starch [36]	Suspended	–	Low pH	1.72 mol/mol glucose
	Corn starch [37]	Heated at 100 °C for 30 min	–	Low pH	1.94 mol/mol glucose
	Wheat straw [38]	120 °C for 90 min	2% H ₂ SO ₂	–	1.19 mol/mol glucose
	Wheat straw [39]	Enzyme treatment	–	–	19.64 mL/g-VS
	Sugarcane bagasse [40]	Raw bagasse heated at 120 °C for 30 min	sulfuric acid (1%, g/v)	Phenolics	62.1 mL/g non-detoxified sugarcane bagasse
Municipal	Fruits and vegetable wastes [41]	Crushed < 2 mm	–	Acetate, Lactate	3.46 mol/mol
	Waste paper [42]	Crushed <0.15 mm and Heat (120 °C for 90 min)	2.2	Furan	140 mL/g sugar
	Waste pastry [43]	Crushed <0.5 mm	–	–	241.4 mL/g glucose
Forestry	Food waste [44]	Crushed <0.5 mm	–	VFAs	57 mL/g-VS (50 °C)
	Poplar leaves [21]	2% vicozyme	–	Furfural	44.92 mL/g dry poplar leaves
	Waste sorghum leaves [45]	heat at 100 °C for 176 min	5.95% HCl	–	47.3 mL/g sugar

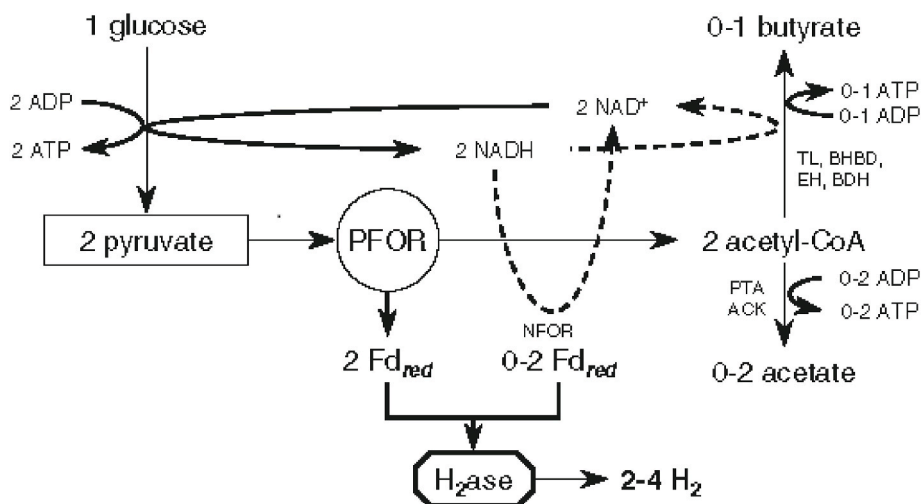


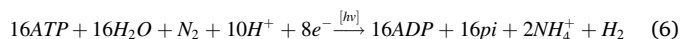
Fig. 2. Fermentation using e.g. *Clostridium butyricum* (Reprinted from Ref. [49]. With permission of Springer Nature).

Enterobacter aerogenes, can also be applied for hydrogen production via fermentation [62]. Unlike *Clostridia*, enteric bacteria primarily yield hydrogen via the decomposition of formic acid and formate, even the exclusive pathway in the case of *E. coli*. Since cleavage is not a redox reaction, it does not influence the redox balance in the fermentation. This conversion route does not suffer from inhibition in case of an increased hydrogen partial pressure since formate cleavage is an irreversible reaction. Furthermore, enteric bacteria are facultative anaerobes, showing high growth rates in the presence of oxygen. After oxygen depletion, an anaerobic metabolism takes over from an aerobic one. Under anaerobic conditions, their growth rate is reduced since less metabolic energy can be extracted from the same substrate. These properties offer the opportunity to develop an industrially interesting scheme of alternating aerobic (fast microbial growth to a high concentration) and anaerobic (high rate hydrogen production) conditions [63].

Controlling the microbial community in the fermenter is necessary to obtaining a sustainable industrial-scale hydrogen production because the used substrate may contain micro-organisms that affect the microbial community within the fermenter, leading to unfavorable conditions and lower hydrogen production rates. Necessary procedures should be taken into consideration, for example, sterilization [64]. Hyperthermophilic archaea (e.g. *Thermotoga neapolitana*) which can be operated at ~ 70 °C and leave little chance of feedstock contaminants becoming established, can also be used for hydrogen fermentation [65].

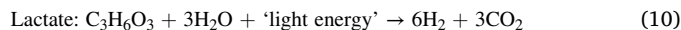
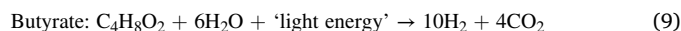
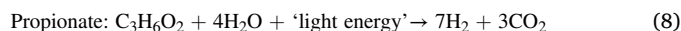
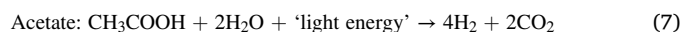
2.3. Photo-fermentation

Fermentation processes which employ light as an energy source for photosynthesis are referred to as photo-fermentation. Comparing to other routes, photo-fermentation has the advantage that light can replace sugars as source of energy, hence reducing the competition for land usage with food crops. The following chemical equation illustrates the hydrogen production via photo-fermentation.



Photosynthetic bacteria such as *Rhodobacter sphaeroides* and *Rhodospirillum rubrum* are commonly applied and use small molecule organic acids as carbon sources [66]. Combining dark-fermentation as the first step and photo-fermentation as the second step can enhance the biohydrogen yield due to the enhanced conversion of substrates to H_2 [67]. In photo-fermentation, the purple non sulphur (PNS) bacteria can utilize the light energy for both the production of ATP and high energy electrons by reverse electron flow to reduce ferredoxin. The ATP and reduced ferredoxin thereafter drive the proton reduction to H_2 by

nitrogenase [68]. The accumulated dark-fermentation VFA can be further converted into hydrogen by photo-fermentation. The reactions from VFAs (mainly acetate, propionate, butyrate and lactate) into hydrogen are shown in Eqs. (7)–(10). An obvious advantage for photo-fermentation is the higher theoretical H_2 yield in comparison with dark fermentation. Moreover, the PNS microorganisms are moreover able to absorb and utilize a wide spectrum of light (400–900 nm), and can also use organic substrates derived from various wastes [69,70].



Among *algae* and some bacteria, hydrogen production capabilities by oxygenic photosynthesis of *Cyanobacteria* are frequently cited [71]. *Purple non-sulphur* (PNS) bacteria (e.g. *Rhodobacter*) are moreover highly promising to hydrogen production via anoxygenic photosynthesis and photo-fermentation [62]. Light within a wavelength range of 400–1000 nm (visible and near-infrared; 400–700 nm; visible) can be used by *algae* and *cyanobacteria* [72].

The industrialization of natural photo-fermentation is restrained by the availability and the distribution of light, since self-shading needs to be minimized in an industrial scale photo-fermenter. The latter restraint imposes a considerable ratio of surface area to volume for an externally illuminated photo-bioreactor. In turn, this results in a material-intensive and hence expensive construction of the photo-bioreactor.

The optimization of light distribution via optic fibers for light transfer in the fermenter is one method that has been recently employed. An additional advantage of this type of photo-bioreactor is the possibility to filter out wavelengths that are of no use for the organisms, hence also controlling radiant heat-gain by dumping excess light.

A light-emitting diode (LED) fermenter was reported to be a potential industrial-size photo-fermenter with a limited area of land occupied; the LED fermenter is able to prevent self-shading and maintain photosynthesis within the fermenter with limited energy consumption and low installation costs. A maximum light conversion efficiency of about 10% has been reported using PNS bacteria. Combining this finding with a maximum efficiency of about 80% for generating electricity from hydrogen (via a PEM fuel cell) and a subsequent maximum efficiency of about 80% for light generation from electricity (via LED), returns are significantly hampered [62].

Photo fermentation furthermore requires specific substrates, i.e. mostly smaller fatty acids such as acetate, propionate and butyrate.

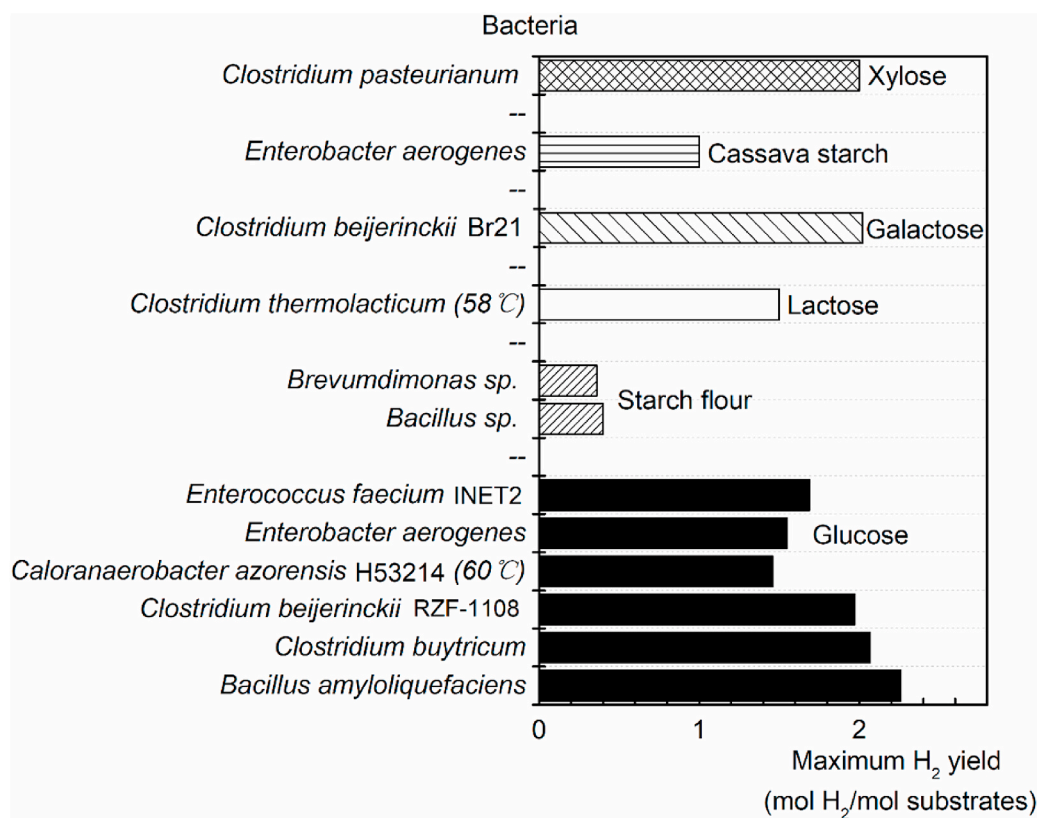


Fig. 3. Single bacteria strains for dark fermentation biohydrogen production, at temperature of 34–37 °C (unless indicated) with substrates xylose [52], cassava starch [53], galactose [54], glucose [50,53,55–59], starch flour [56,60] and lactose [61].

Towards the targets of fuel or energy hydrogen production, artificially lit photo-bioreactors such as the LED-fermenter were proven non-viable.

2.4. Combined fermentation

As briefly mentioned before, there are studies dealing with combining dark- and photo-fermentation and these studies consider the combined fermentation as the most promising technique for industrial fermentation of hydrogen because of its economy and because it reduces the amount of by-products of the fermentation process [62,73,74]. The major advantage of applying a combined fermentation is due to its capability for the photosynthesis step to reuse the otherwise useless organic acids. However, combined fermentation also faces the issues to optimize the design of the reactor and minimize the energy consumption, both major drawbacks of photo-fermentation.

Chen et al. [75] combined dark and photo fermentation for overall hydrogen yield and COD reduction. The dark fermentation effluent mainly comprised acetate and butyrate, and *Rhodospseudomonas palustris* WP3-5 was used as inoculum in photo fermentation. The total hydrogen yield could be enhanced from 3.80 mol H₂/mol sucrose to 10.02 mol H₂/mol sucrose, and a high COD removal of 72.0% could be obtained. They further found that acetate was the most favorable carbon later source for *Rhodospseudomonas palustris* WP3-5 in photo fermentation, whereas inhibition occurred when butyrate was used as the carbon source [76]. Chookaew et al. [77] investigated a two-stage process in which *Klebsiella* sp. TR17 was used in the first stage (dark-fermentation) and *Rhodospseudomonas palustris* TN1 was applied in the second stage (PF) to convert crude glycerol to hydrogen. In the first stage, a hydrogen yield of 5.74 mmol H₂/g COD consumed was obtained. In the second stage, a hydrogen yield of 0.68 mmol H₂/g COD consumed was achieved with addition of yeast extract (2.3 g/L), NaHCO₃ (0.63 g/L), and glutamate (2–8 mmol/L) in 5-fold diluted dark-fermentation effluent,

resulting in a total hydrogen yield of 6.42 mmol H₂/g COD consumed. Other researchers succeeded in converting the dark-fermentation effluent of hydrogen using photo-fermentation [78–80]. These efforts demonstrated that photo-fermentation was an effective in the further valorization of dark-fermentation effluent.

3. Specific problems and bottlenecks involved in the biochemical production methods (like yields, costs, and biomass waste)

This section will firstly demonstrate the pathways of hydrogen fermentation and then discuss the different parameters that affect the process as a result of the fundamental pathway. The overall assessment will highlight the bottlenecks involved in the hydrogen production, and dealt with in detail in section 4.

3.1. The fundamental metabolic pathways of dark fermentation

To investigate the biological effects during dark fermentation, Fig. 4 illustrates the metabolic pathways, where *Clostridium* sp. and *Enterobacter* sp. are the main species that are commonly used in bio-hydrogen production.

The metabolism can be divided into two separate pathways: the facultative anaerobic metabolism, such as through *Escherichia coli* (as indicated by PFL pathway, pyruvate formate-lyase) and strict anaerobic metabolism, through *Clostridium* (as indicated by PFOR pathway, standing for pyruvate: ferredoxin oxidoreductase).

Glucose in both routes breaks into pyruvate through standard glycolysis, in which process the NAD is reduced to NADH and the conversion of ADP to ATP takes place. The key intermediate is pyruvate, since its degradations differ from PFOR and PFL. In principle, formate is formed when facultative anaerobes degrade pyruvate, while acetyl-CoA

is transformed through the action of PFL. Strict anaerobes produce acetyl-CoA, CO₂, and reduced ferredoxin using PFOR (pyruvate: ferredoxin oxidoreductase). Hence, in a facultative anaerobic metabolism pathway, the *fhl* complex which possesses Ni-Fe hydrogenase is responsible for producing hydrogen from formate. Alternatively, reduced ferredoxin promotes the hydrogen production by a FeFe hydrogenase. The by-product is principally ethanol in facultative fermentation, and ethanol, butyric acid, butanol and acetone for the strict anaerobic pathway depending on the microorganism and the physical fermentation conditions.

3.2. The parameter-response of fermentation

The process of fermentative hydrogen production is complex. The H₂ productivity depends mainly on the inoculant, the cultures, the substrates, and the addition of trace elements [13].

3.2.1. Effect of inoculum

Different inoculants have been studied for H₂ production, among which *Enterobacter sp.*, *Bacillus sp.* and *Clostridium sp.* distinguished by its gram-negative, rod-shaped and strict anaerobic nature. *Clostridium sp.* converts glucose to VFAs, H₂ and CO₂. The typical species are *C. butyricum*, *C. thermolacticum*, *C. pasteurianum* and *C. bifementans* [62, 72]. *Enterobacteriaceae* are gram-negative, rod-shaped but facultative anaerobes.

Almost all studies used pure cultures of bacteria in batch mode with six-carbon sugars (e.g. glucose) as substrate in major cases. Studies utilizing five-carbon sugars, such as xylose show low yield though it is a potential solution to release the pressure from the food crisis as five-carbon sugars account for little of food supply. In this condition, renewable feedstock of organic wastes is a more desirable substrate, however demanding a diversity of hydrogen producing microorganisms due to its complexity. Microorganisms which are capable of H₂ production exist wildly in soils, wastewater treatment sludge and compost.

Fig. 5 illustrates the production yield of H₂ with different microbial strains, which show different capabilities as the yield varies from 1 to

2.8mol H₂/mol [50,82–93].

3.2.2. Effect of the cultures

Fermentation with pure cultures has a limited metabolic capacity, therefore mixed cultures were proposed since they extend the range of substrates so that the VFAs produced in dark fermentation can further be used in photosynthesis and converted to hydrogen. There are studies dealing with two combination patterns, i.e. sequencing batch operations of dark- and photo-fermentation, and their combination [94].

Combining *C. butyricum* and *Rhodobacter sp.* produces 4.5 mol H₂/mol glucose, higher than the yield in a sole dark fermentative (1.9 mol H₂/mol glucose) and the obtained value in two consecutive steps (3.7 mol H₂/mol glucose) [95]. The maximum H₂ yield and production rate reported when using the combined and sequencing batch operation is 6.6–7.2 mol H₂/mol glucose and 1.55 mmol H₂/L culture/hr respectively.

Bao et al. [60] however reported a successful fermentation that combines hydrolysis and hydrogen generation in a single bioreactor. The strains include *Bacillus sp.* which is responsible for starch hydrolysis and *Brevumdimonas sp.* being in charge of hydrogen synthesis. The interspecies cooperation allows to produce H₂ in a single reactor with cumulative yield up to 1.04 mol H₂/mol glucose. Table 2 demonstrates the studies on various culture modes which also showed the quantity of hydrogen produced. Higher hydrogen yields are reported for separate hydrolysis and subsequent fermentation.

3.2.3. Effect of substrates

Substrates have a definite influence on the fermentation process due to their different biodegradabilities. Glucose, maltose and xylose are readily used, while other substrates, for example starch, require a preliminary transformation into glucose or maltose, either by acid or by enzymatic hydrolysis. Furthermore cellulose is the most difficult to use as most microorganisms cannot directly or indirectly consume cellulose. On the other hand, the carbohydrate-rich wastes feedstock such as waste water from the sugar mills, from breweries, from cassava processing and others, can to a large extent reduce the cost of bio-H₂. Cassava is a

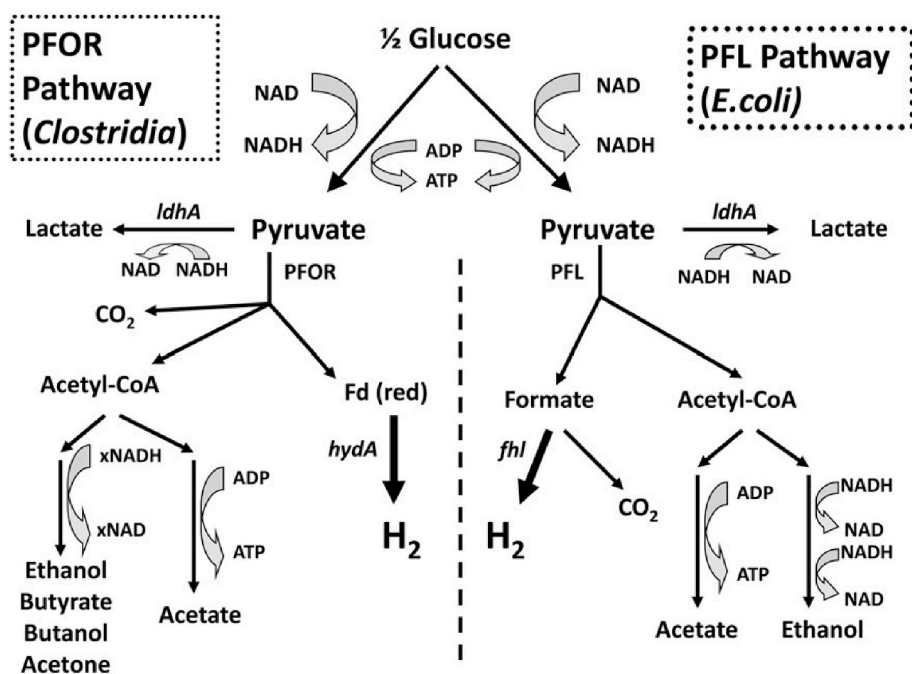


Fig. 4. Metabolic pathways within the hydrogen dark fermentation (Reprinted from Ref. [81]. With permission of Elsevier).

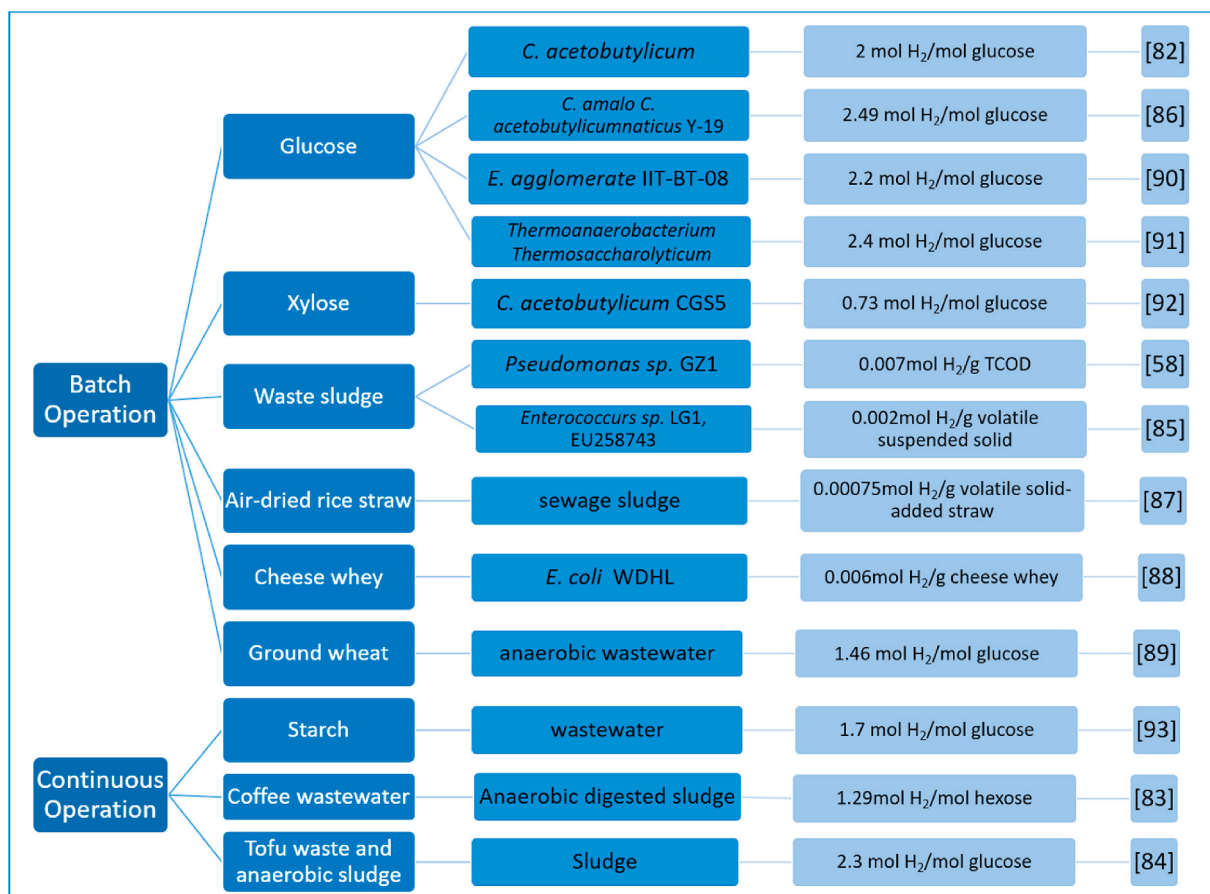


Fig. 5. Different bacterial cultures in batch or continuous fermentative H₂ production modes.

promising hydrogen production feedstock due to the fact that it can be planted on sterile soil [102] and is not used for food at some production locations. The maximum production yield using cassava flour under optimum operating conditions was reported as 1.72mol H₂/mol glucose [103]. Moreover, the waste water from the cassava starch manufacture is also rich in carbohydrates with a high BOD and COD (»10 g/L), which makes it suitable as feedstock. The fermentation process is simultaneously part of the wastewater treatment, which makes it a win-win situation for the cassava starch production.

In addition to substrates summarized in Fig. 3, additional studies with different substrates are illustrated in Table 3.

3.2.4. Effects of trace elements

Enzymes are the specific performers of all the metabolism and bio

reactions including the hydrogen production reactions. Trace elements, for example metal ions (Na⁺, Mg²⁺, Zn²⁺ and Fe²⁺) are co-factors of enzymes, thus they are essential factors for the hydrogen synthesis: iron and nickel are necessary elements of hydrogenase [37]; magnesium is the activating agent for kinase and synthetase [37]; and some reducing amino acids, for example L-cysteine, are capable of maintaining the oxidation-reduction potential (ORP) [37].

Hydrogenase is involved in both pathways, which are [Fe-Fe] hydrogenase in the PFOR and [Ni-Fe] hydrogenase in the PFL [68,113, 114]. The [Ni-Fe] hydrogenase is significantly present in hydrogen-producing bacteria and it has a less sensitive inhibitory effect on oxygen in comparison with [Fe-Fe] hydrogenase, therefore Fe²⁺ and Ni²⁺ are the two significant trace elements affecting hydrogen fermentation production.

Table 2

Hydrogen production using different cultures, in batch (B) or continuous (C) operating mode.

Substrate and its concentration	Inoculums	Produced H ₂ (mol H ₂ /mol glucose)	
Glucose, 9 g/L	<i>C. butyricum</i> + <i>R. coprophilus</i> <i>Pseudomonas</i> RLD-53	1.98	B [96]
Acid hydrolysis of wheat starch, 5 g/L	<i>Rhodobacter sphaeroide</i> -RV	1.23	B [97]
Hydrolyzed starch, 26 g/L	<i>C. butyricum</i> CGS2	1.5	C [98]
Discarded wheat starch, 5 g/L	<i>C. acetobutylicum</i> + <i>Rhodobacter sphaeroide</i> -RV	0.6	C [99]
Wheat starch, 10 g/L	Anaerobic digestion sludge	1.14	B [100]
Corn starch, 20 g/L	Excess waste activated sludge	0.92	C [101]
Corn starch, 10 g/L	Mixed cultures	1.04	B [60]
Wheat starch, 10 g/L	Dark fermentation + <i>Rhodobacter sp.</i>	185 mL H ₂ g VFA	C [94]

Table 3

Effect of different substrates on the hydrogen yield.

Inoculum	Substrates	Maximum hydrogen yield	Refs.
<i>C. acetobutylicum</i> CGS2	Starch	9.95 mmol H ₂ /g COD	[104]
Municipal sewage sludge	Xylose	2.25mol H ₂ /mol xylose	[105]
<i>C. Pasteur</i> CH ₄	Sucrose	2.07mol H ₂ /mol hexose	[92]
<i>C. thermolaticum</i>	Lactose	3.0 mol H ₂ /mol lactose	[61]
Cow dung compost	Cornstalk wastes	149.69 mL H ₂ /g TVS	[106]
Class septicumM-21	Chitin wastes	2.2 mol H ₂ /mol substrate	[107]
Cow dung compost	Beer lees	68.6 mL H ₂ /g TVS	[108]
<i>C. thermocellum</i> 27405	Cellulose biomass	2.3mol H ₂ /mol glucose	[109]
Anaerobic sludge	Food waste	1.8mol H ₂ /mol hexose	[110]
<i>E. cloacae</i> E82005	Molasses	3.5mol H ₂ /mol sucrose	[111]
Anaerobic Sludge	Dairy wastewater	31.7 mmol H ₂ /g COD	[112]

Research showed that iron and sulphur influence the function of proteins by acting as electron carrier in the oxidation of pyruvate to acetyl-CoA, CO₂ and H₂. Wang and Wan reported that iron addition boosted the synthesis of hydrogen to the maximum yield of 2.33 mol/mol glucose at 350 mg/L of Fe²⁺ [115]. Moreover, iron could induce metabolic alteration: experiments revealed that the amount of Hydrogen produced increased to 3.06 mol/mol glucose from 2.93 mol/mol glucose after adding 25 mg/L FeSO₄·7H₂O, and vice versa.

Table 4 summarizes how adding trace elements affects the hydrogen production. Whereas bio-hydrogen production essentially requires the presence of sufficient quantities of essential micro-nutrients for bacterial metabolism during fermentation (such as metal ions and trace elements), the enhancement efficiencies of individual or compound nutrients are different.

3.2.5. Overall assessment

As far as photo-fermentation is concerned, its negative energy balance when using an artificial light source needs further investigations in terms of technical and economic respects.

Biological production of H₂ by dark fermentation of wastes (primary route) and non-food biomass (secondary route) can facilitate the proposed green, sustainable hydrogen economy. It is currently drawing great attention since no additional energy source is needed, and since the technique is capable of using various feedstock, such as waste water and process residuals. The core barrier now is the attainable yield in the typical mesophilic fermentation: glucose has a potential equivalent of 4 mol H₂/mol glucose. Through fermentation, between 25 and 50% of the available hydrogen is released as H₂ [110,118]. One should moreover also consider that the mass balance of the reaction is not in favor of H₂ (despite its 2 mol/mol glucose), but results in a waste water with very high concentrations of VFA's produced (acetate, butyrate, propionate), hence with a high COD, needing further treatment. Given the ideal yield of 4mol H₂/mol glucose, provided the density of gasoline is 0.72 kg/L, and at a heat capacity of gasoline and hydrogen of 44 MJ/kg and 143 MJ/kg respectively, a vehicle will consume 1.5 kg hydrogen per 100 km (it is equivalent to 7 L gasoline per 100 km). At the production of 4 mol

Table 4Effects of adding of trace elements on the H₂ production.

Elements		Remarks	Ref.
Ni ²⁺	Within Ni ²⁺ 0–50 mg/L, H ₂ production increases as Ni ²⁺ increases, and decreases as the Ni ²⁺ increases beyond 50 mg/L		[116]
Ni ²⁺	H ₂ production was increased by 71% by adding Fe ²⁺ and Ni ²⁺ comparing to the blank sample and reached the maximum at 50 mg/L of Fe ²⁺ and 25 mg/L of Ni ²⁺ .	glucose as substrate an anaerobic continuous flow stirred tank	[117]
L-cysteine Fe ²⁺ and L-cysteine	Adding L-cysteine (0.1–1.0 mM) improves H ₂ yields H ₂ yield is increased to maximum 1982 mL and 1.94 mol H ₂ /mol glucose	Relative enhancement effect: Fe ²⁺ > L-cysteine > L-cysteine + Ni ²⁺ > L-cysteine + Fe ²⁺ > L-cysteine + Mg ²⁺	[37]
Ni ²⁺	H ₂ production was reduced at Ni ²⁺ concentrations above 20 mg/L		[60]

H₂/mol glucose, or 8 g/180 g glucose, the production of 1.5 kg of H₂, needs a theoretical input of 33.8 kg of glucose. At lower conversion efficiencies, the amount of glucose consumed will increase. This low efficiency, together with the required further waste water treatment, will prevent the production of H₂ to compete with fossil fuel for a long period in future. A better conversion and/or an efficient use of the by-products (mainly acetate and butyrate) are the key factor to the future bio-H₂ success.

4. Potential solutions to overcome the bottlenecks and recommended actions towards a better future for biochemical hydrogen production

Although biochemical fermentation is an attractive way of producing bio-hydrogen since a variety of available wastes or biomass can be used, its industrial application is at present hampered by the low yields obtained.

To improve the yield of hydrogen, studies are being conducted in different areas, including mainly: metabolic engineering; third stage fermentation of butyric/acetic acid; separation/upgrading of the acids; and membrane separation of hydrogen.

4.1. Metabolic engineering

Metabolic engineering has been recognized as having a potential to enhance the hydrogen yield. The key obstacles of fermentation are the constraints introduced by the metabolic pathways involved. The fundamental metabolisms leading to H₂ production were outlined in 3.1. Current research investigates increased yields by either modifying the existing pathways, or by metabolic engineering to introduce new enzymes and/or pathways to overcome thermodynamic or metabolic barriers to increase the yields.

Fig. 6 below illustrates different strategies to maximize yields of present hydrogen synthesis pathways by eliminating reactions that compete for the same substrate, or by eliminating the activity of any uptake hydrogenases that could be present.

Inactivating competing reactions and manipulating culture conditions has led to higher H₂ yields, close to values predicted by metabolic schemes, although the final target of H₂ production levels beyond present limits needs further investigation.

H₂ production when using *Clostridium* bacteria could be fostered by disabling the uptake of hydrogenase, or disabling the oxygen system. Such actions will result in a more robust hydrogen production, where the hydrogen yield of the dark-fermentation step could be enhanced [119–121].

Researchers have proposed to introduce new pathways, however all of them end up with low yield due to various factors. One attempt for *E. coli* intended to express a highly active [Fe–Fe] hydrogenase (hydA) from various sources, but it failed since *E. coli* does not possess the specific genes (which encode the required maturation factors) required for the expression of hydA, even with the assistance of co-expressed hydEFG [122]. Other modifications have been tried and provided

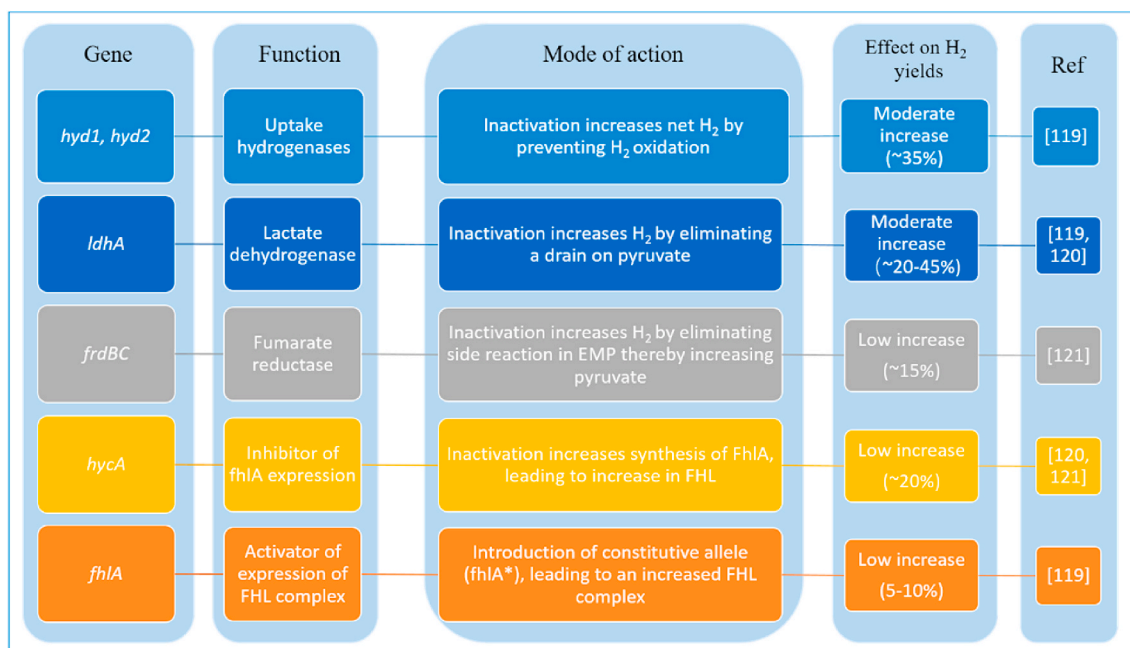


Fig. 6. Targets of genetic modification of common pathways.

negative conclusions till now. Different metabolic engineering strategies are summarized in Table 5.

Using a reverse electron flow was suggested as alternative solution: the reduction of ferredoxin with NADH could generate enough reducing power to promote hydrogen production by hydrogenase [132]. In this process, it is necessary to overcome the thermodynamic barrier with energy input. A small amount of respiration could be used to overcome the barrier by creating an electrochemical gradient to favor the ferredoxin reduction. This method needs further investigation.

Conclusively, a possible modification of the system could drive it to higher bio-hydrogen yields. However further investigations are needed.

4.2. Third stage fermentation of butyric/acetic acid

As discussed above, the waste water of dark fermentation is rich in butyric/acetic acid and is not environmentally friendly. These volatile fatty acids have to be treated either by VFA recovery or by a following stage of photo fermentation, that can utilize the residual VFA and increase the cumulative yield. The overall yield of hydrogen in such a two-stage operation exceeded the yield of a single stage production process [133]. Bao et al. [37] reported a pH ~4 at the termination of the mixed culture fermentation. Fig. 7 summarizes the pH and the quantities of residual VFA. It appears that the pH is between 4 and 8 due to the generation of VFA. Different substrate were used, i.e. food waste [110], glucose [134], cornstalk waste [106], cattle dung and sludge [73], steam exploded corn straw [135], fruit vegetable waste [136], rice waste

[137], and sewage sludge [138,139]. Reference effluent composition data are converted from mg/L, g/L, % values to total VFA concentrations, given in mM/L.

Experiments revealed that malate and lactate were the most favorable substrates, with the highest H₂ production rates in photo-production [140]. Uyar et al. [141] investigated the growth and hydrogen production of *Rhodobacter sphaeroides* O.U. 001 in media containing mixed VFAs (malate, acetate, propionate, butyrate and lactate): their results demonstrate that the highest H₂ production rates during of dark fermentation were obtained in malate (24 mL hydrogen/L reactor h). It was moreover observed that the bacteria sequentially consumed acetate, propionate and then butyrate. For the different VFAs tested, the butyrate H₂-efficiency was lower due to the competitive production of PHB. The substrate conversion efficiencies were globally between 14 and 50% [142].

4.3. Upgrading of the VFAs

VFAs are obtained as key intermediates in dark fermentation processes. As discussed previously, acetate is the most favorable for VFA fermentation, which makes the upgrading of volatile fatty acids a possible pretreatment or biological facilitation to hydrogen production. The upgrading of acids mainly targets on the low or even negative cost of feedstock, such as sludge, organic wastes, meaning the required cost is low, the target end product being VFAs, for example acetate via an anaerobic process. Fig. 8 summarizes literature data for soluble

Table 5
Different metabolic engineering strategies to increase hydrogen production.

Strains	Metabolic engineering strategy	Improved H ₂ production (%)
<i>E. coli</i> K-12 BW25113 [123]	Protein engineering of large subunit of hydrogenase 3 (<i>hycE</i>)	800 (compared with wild-type strain)
<i>E. coli</i> K-12 BW25113 [124]	Inactivation of hydrogenase 1 and hydrogenase 2	200
<i>Caldicellulosiruptor bescii</i> [125]	Deletion of lactate dehydrogenase gene (<i>ldh</i>)	21–34
<i>E. coli</i> [126]	Heterologous expression of HupSL hydrogenase from <i>Rhodobacter sphaeroides</i>	209
<i>Enterobacter aerogenes</i> [127]	Homologous overexpression of NAD synthetize gene <i>hadE</i> and deletion of phosphoenolpyruvate carboxylase gene (<i>ppc</i> and <i>hycB</i>)	301
<i>Klebsiella oxytoca</i> HP1 [128]	Homologous overexpression of two hydrogenase subunits (<i>hycE</i> and <i>hycG</i>)	90.5
<i>Clostridium tyrobutyricum</i> [129]	Homologous overexpression of hydrogenase gene (<i>hydA</i>)	150
<i>C. pasteurianum</i> [130]	Homologous overexpression of hydrogenase (<i>hydA</i>) and glycerol dehydrogenase (<i>dhaDI</i> and <i>dhaK</i>)	170
<i>C.tyrobutyricum</i> [131]	Inactivation of acetate kinase (<i>ack</i>)	150

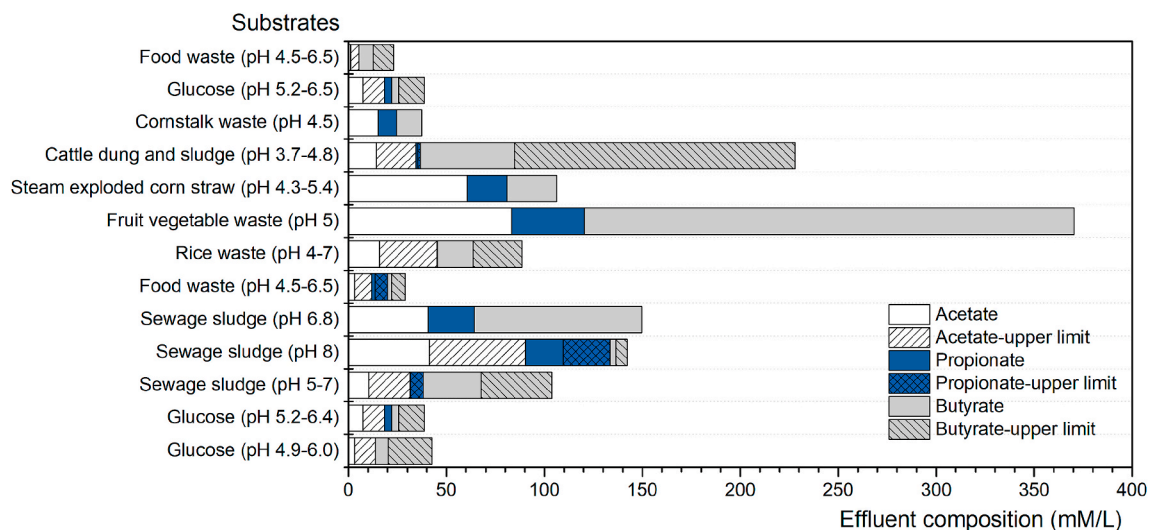


Fig. 7. VFA composition of the effluent.

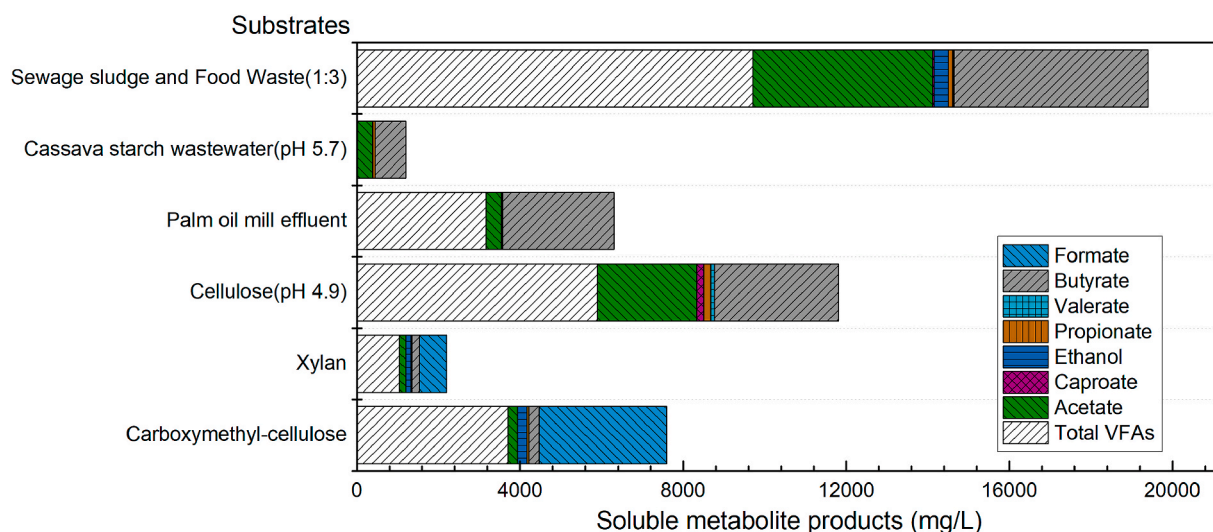


Fig. 8. Soluble metabolite products of effluent from dark hydrogen fermentation. Carboxymethyl-cellulose [143], Xylan [143], Cellulose [144], Palm oil mill effluent [39], Cassava starch Wastewater [33], Mixture of sewage sludge and food waste (1:3) [145].

metabolites, produced during dark fermentation.

The anaerobic process can be described by four steps, being (i) hydrolysis, where larger polymers are decomposed by enzymes; (ii) fermentation, where acidogenic fermentation is dominant and acetate is the main end product (VFAs are also produced along with CO₂ and H₂); (iii) the breakdown of VFAs to acetate and H₂ by acetogenesis; and finally (iv) the conversion of acetate, formaldehyde, hydrogen and carbon dioxide into methane, carbon dioxide and water by methanogenesis.

One of the two most important threats is the suppression of the methanogenesis step. Dictor et al. [146] found that methanogenesis can be inhibited during anaerobic electro-stimulation (application of a weak current to hydrogen producing bacteria) with promoted degradation of organic waste, thus leading to an enhanced hydrogen production.

Dark fermentation is an alternative of the common anaerobic digestion but where anaerobic fermentation is stopped by suppressing methanogenesis, hence not converting VFA to methane or to hydrogen.

A different route that certainly merits further investigation is the recovery and separation of the VFAs, for use in chemical transformations or as raw material. Both acetates and butyrates can be transformed into esters, then separated and purified as chemical feedstock.

4.4. Membrane purification of hydrogen

As the last step of hydrogen production, its purification is very important with Pressure Swing Adsorption, cryogenic distillation, and membrane separation as possible solutions. The first two processes are energy intensive [147], and current research focuses on membrane separation with polymeric and non-polymeric materials [110,148–152].

If proven to be viable in real operating conditions, membrane separation will attractively compete with the more mature technologies of pressure swing adsorption and cryogenic distillation. Apart from the high energy consumption, a cryogenic system can only practically achieve moderate hydrogen purities (~95%) [153].

Hydrogen separation membranes were previously reviewed [149], and the operating conditions and performance of different membranes is illustrated in Fig. 9. Inorganic membranes can cope with more severe operating conditions their organic counterparts.

As illustrated in the figure, the selectivity and working flux both are low for dense polymer membrane. Metallic membranes have a very high selectivity and flux. Highly pure hydrogen can be obtained through using dense metallic membranes. However the metal Pd is expensive, though thin film membranes can to some degree reduce the cost. Thin

Membrane types	T (K)	H ₂ selectivity relative to CO ₂	H ₂ flux (mol/m ² s bar)	Stability issues	Poisoning issues	materials	Transport mechanism
Dense polymer	<373	low	low	Swelling, compaction	HCl, SO _x	polymers	Solution diffusion
Microporous ceramic	473-873	5-139	0.06-0.3	Stability in H ₂ O		Silica, alumina, zirconia, titania, zeolites	Molecular sieving
Dense metallic	573-873	>1000	0.06-0.3	Phase transition	H ₂ S, HCl, CO	Palladium and its alloys	Solution-diffusion
Porous carbon	773-1173	4-20	0.01-0.1	brittle	Strong absorbing vapors	carbon	Solution-diffusion, molecular sieving
Dense ceramic	873-1173	>1000	0.006-0.08	Stability in CO ₂	H ₂ S	Proton-conducting carbon	Solution-diffusion

Fig. 9. The operating conditions and performance of different membranes.

membranes also increase the hydrogen flux. The drawback of a metallic membrane is its sensitivity to some gases, such as CO, H₂S, thus needing gas pretreatment. Ceramic membranes are inert to hazardous gases, are resistant to high pressure and temperature, thus making it attractive to systems that operate at increased pressures, where permeabilities are considerably increased. However, due to its working mechanism, microporous ceramic membranes can never reach the 100% purity obtained by thin-film-palladium or ion-transport membranes.

4.5. Potential and challenges

Bio-hydrogen production through fermentation has advantages over other approaches, because abundant waste biomass can be used without increasing the amount of greenhouse gases in the atmosphere, and moving closer to a “hydrogen economy”. If 88% of the cost of bio-hydrogen through fermentation of glucose is attributed to the feedstock [154,155]. It is important to utilize cost-effective substrates.

The low substrate conversion (usually <30%) and low hydrogen yield which is thermodynamically limited to maximum of 4 mol H₂/mol hexose, are considered to be the main limitations of biohydrogen [156]. The energy conversion efficiency can be improved by integrating fermentation with other techniques such as anaerobic digestion or efficiency can be improved by integrating fermentation with other techniques such as anaerobic digestion or bio-electrochemical systems. To improve the performance of an integrated system in using wasted biomass, the selection of effective bacteria, construction of efficient strains and optimization of the process conditions have been studied, i. e., the utilization of high productive bacteria like *E.coli* or *R.sphaeroides* [157].

Currently, most of studies on dark-fermentation were conducted at lab scale. However, from an economic point of view, a continuous process is required for constant biohydrogen production at large scale. Additional research is also required (1) to explore cost-effective bio-hydrogen using abundant wasted biomass, (2) to develop an energy efficient, environmentally friendly and inhibitor-free pretreatment approaches when cellulosic materials are used as feedstock, (3) to isolate new bacterial species or obtain robust microbes by modifying the pathways of present microorganisms using genetic methods, (4) to assess the economic feasibility of biohydrogen production from waste

biomass (i.e., life cycle analysis), (5) to integrate the up- and down-stream technologies for multi-outputs from waste biomass. The most possible commercial establishment for biohydrogen production can be at a position near to a wastewater treatment plant, with stable and sufficient supply of feedstock. However, only wastewater supply will not be enough for continuous biohydrogen production since the content of organic substrate of wastewater will be insufficient for dark-fermentation. Thus addition of other organic substrates such as agricultural wastes and municipal organic wastes will be required.

Although the present review focused on the bio-hydrogen production, it is interesting to compare these current lab-scale systems with commercial or significantly developed H₂ production systems that utilize renewable and non-renewable resources. Fig. 10 illustrates the 3 different strategies, using fossil fuels, nuclear energy and bio-energy resources. Within the fossil fuel solutions, hydrocarbon reforming and pyrolysis/gasification are widely applied on a commercial scale. Nuclear energy applications consider high temperature water splitting and electrolysis. The renewable energy routes comprise two alternative pathways for using diverse biomass species in either thermo-chemical processes (mostly pyrolysis, gasification and liquefaction), or in fermentation processes (indirect bio-photolysis, dark fermentation, photo-fermentation, sequential dark and photo-fermentation). While the thermo-chemical processes can be considered of commercial scale, fermentation could see enhanced development on a medium term. Electrolysis, associated with some of the renewable electricity generation is commercially proven.

Although costing data are scarce and widely differing among published data, a tentative comparison is presented in Table 6. Cost components related to H₂ storage, transportation and utilization are not included. It should be remembered that efficiencies for steam reforming are 70–85%, 60–75% for coal gasification, 50–70% for electrolysis and 35–50% for biomass gasification. Efficiencies of fermentation processes are still below 5%.

It is clear that currently the most economic sources of H₂ are fossil fuels and biomass. A kilogram of hydrogen has nearly the energy content of one gallon of gasoline. The cost of hydrogen per kilogram is hence directly comparable to the cost of a gallon of gasoline. From the data, it is clear that advanced nuclear techniques need major improvements to be economically viable. Also renewable energy (wind, solar) driven

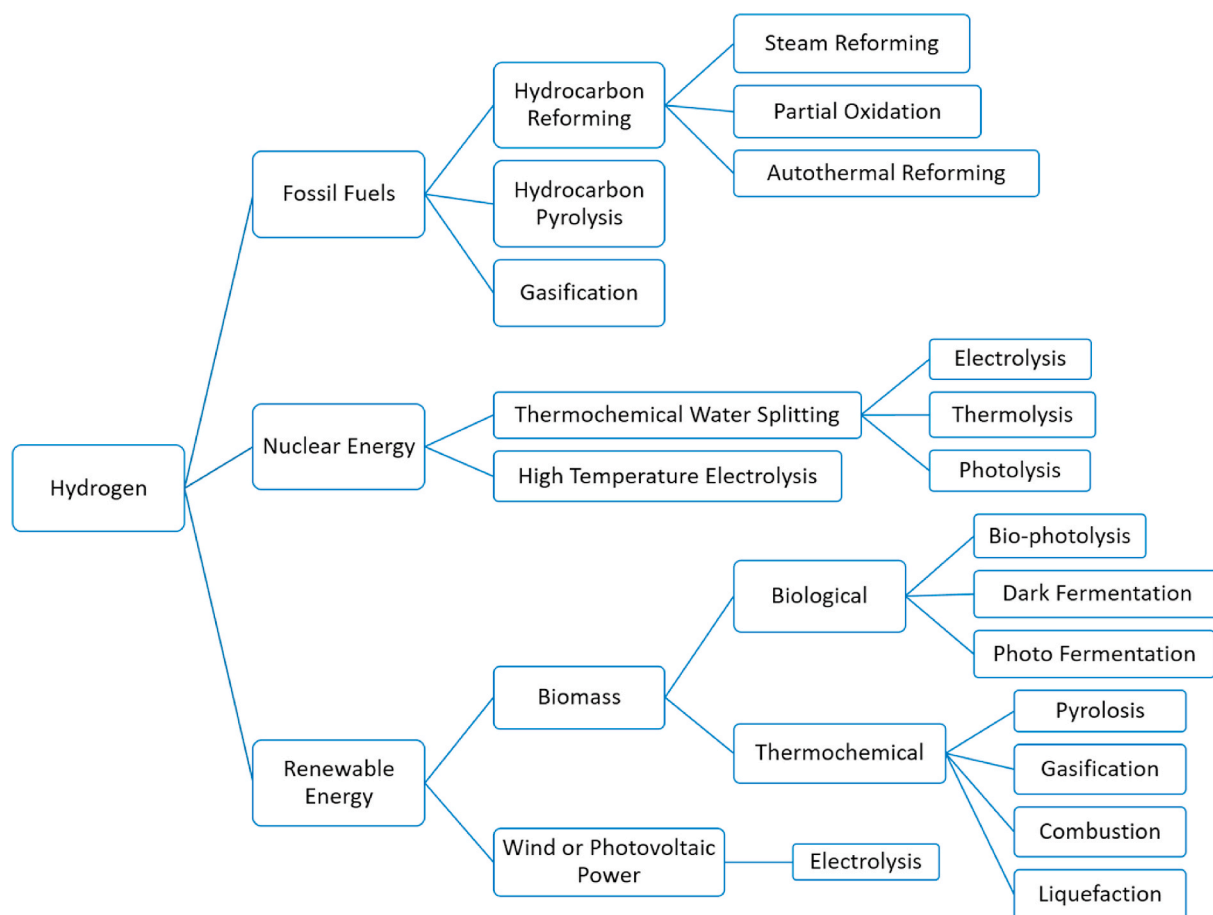


Fig. 10. Technologies for producing H₂ from fossil fuel, nuclear energy or renewable energy resources or feedstock.

Table 6
Operating and cost data for hydrogen production from renewable and non-renewable resources.

Processes	Energy source	References	Feedstock Cost	Plant Output (t H ₂ /h)	H ₂ cost (\$/kg)
Steam Methane Reforming (SMR)	Natural gas	Dincer and Acar, 2014 [158]; Acar and Dincer, 2015 [159]; Kalamaras, 2013 [160]; Penner 2006 [161]; Rutkowski, 2005 [162]	9.48 \$/GJ	9.8–14.2	1.8–3.0
SMR with CO ₂ sequestration	Natural gas	Rutkowski, 2005 [162];	9.48 \$/GJ	14.2	2.3
Coal Gasification (CG)	Coal	Kreutz et al., 2002 [163]; Rutkowski, 2005 [162]	1.15–1.26 \$/GJ	10.6–32.1	0.8–1.3
CG with CO ₂ sequestration	Coal	Kreutz et al., 2002 [163]; Rutkowski, 2005 [162]; Dincer and Acar, 2014 [158]; Acar and Dincer, 2015 [159]	1.15–1.26 \$/GJ	10.6–32.1	0.9–1.7
Nuclear Energy and Electrolysis	Nuclear	Petri et al., 2006 [164]; Dincer and Acar, 2014 [158]; Acar and Dincer, 2015 [159]	~0.048 \$/kW h	0.04	4.2–7
Sulphur-iodine thermochemical water splitting	Nuclear	Richards et al., 2006 [165]; Schultz, 2003 [166]	Not available	24.3–30.1	1.75–2.01
Wind turbines and electrolysis	Wind	Bockris & Veziroglu, 2006 [167]; Levene et al., 2006 [168]; Dincer and Acar, 2014 [158]; Acar and Dincer, 2015 [159]	0.038 to 0.045 \$/kW h	0.04	5.6–7.5
Photovoltaics and electrolysis	Solar	Glatzmaier et al., 2010 [169]; Dincer and Acar, 2014 [158]; Acar and Dincer, 2015 [159]	0.03 to 0.05 \$/kWh	0.06–14.8	6.1–9.0
Solar Power Tower and electrolysis	Solar	Glatzmaier et al., 2010 [169]; Kolb et al., 2007 [170]	0.08 to 0.10 \$/kWh	16–26.3	5.1–6.5
Gasification	Biomass	Mann, 2005 [171]; Dincer and Acar, 2014 [158]; Acar and Dincer, 2015 [159]	16.5–46.3 \$/t	0.08–8.1	1.0–2.0
Pyrolysis	Biomass	Padro and Putsche, 1999 [172]	16.5–46.3 \$/t	0.11–30.4	1.0–2.0
Dark Fermentation	Biomass	Jeffrey, 2010 [173]	Various resources	Lab-scale only	2.6
Photo Fermentation	Solar	Demirbas MF, 2006 [174]	Various resources	Lab-scale only	2.8

techniques are still too expensive, despite being currently promoted on a large scale to utilize excess electricity produced by wind turbines or photovoltaics in periods of low electricity demand of the grid. Gasification and pyrolysis of biomass in its different forms can be attractive,

especially due to the volatility of fossil fuel prices. Bio-hydrogen production by fermentation is still rather expensive, but one should remember that only lab-scale data are currently available.

5. Conclusions and recommendations

Large industrial-scale of hydrogen production from biomass or carbohydrates by fermentation, though undoubtedly desirable and favored, is however still at the level of laboratory or pilot scale. Strategies for industrial-scale production, at an economically viable level, need to be developed, and further research is still needed. A wide spectrum of wasted biomass of industrial, agricultural, municipal and forestry origins can be considered to be used as substrate. Although results are interesting, and confirm the possibility of generating bio-hydrogen, all techniques suffer from 3 main drawbacks, i.e. (i) a low production yield of H₂ (a few mol H₂/per mol of equivalent glucose only in the case of fermentation); (ii) the production of a liquid waste stream rich in VFAs and hence needing further treatment when fermentation is used.

The present work reviewed the literature relative to dark fermentation, photo-fermentation, and combined processes. Dark-fermentation is an environment-friendly and cost effective approach of used for waste biomass. To improve the performance of dark-fermentation, it is essential to use several microorganisms capable of high hydrogen yield such as *Bacillus amyloliquefaciens* and *C. pasteurianum* and to use some advanced techniques of co-culture fermentation. The application of mutant strain obtained from genetic engineering becomes a promising trend in dark-fermentation. The development of integrated systems of dark-fermentation with other technologies such as anaerobic digestion is important for valorization of dark-fermentation effluent, making the production of biohydrogen profitable and sustainable.

Although literature offers some solutions to the problems, as outlined in Section 4, these solutions are either incomplete, economically debatable, or in initial stages of assessment.

To enhance the future of bio-hydrogen, an important step forward would involve the further use and valorization of the residual waste streams produced by fermentation. At current market values of C₂, C₃ and C₄ chemicals, it is certainly worth focusing research efforts on the recovery and additional use of VFAs and minor organic compounds formed by bio-H₂ fermentation.

Credit author information

Jan Baeyens, Conceptualization, Writing - original draft, Writing - review & editing, Project administration, Huili Zhang; Investigation, Methodology, Writing - original draft, Jiawei Nie; Data Curation, Visualization, Lise Appels, Data Curation, Visualization, Writing - review & editing, Raf Dewil; Writing - Review & Editing, Visualization, Supervision, Renaud Ansart, Writing - Review & Editing, Validation, Yimin Deng, Methodology, Writing - original draft, Writing - review & editing, Visualization.

Declaration of competing interest

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

Acknowledgement

The authors acknowledge financial support by the Fundamental Research Fund for the Central Universities (No. buctrc201726). Additional support was obtained from the Beijing Advanced Innovation Center for Soft Matter Science and Engineering of the Beijing University of Chemical Technology.

References

[1] Consulting IHS. Chemical economics report-hydrogen. <https://ihsmarkit.com/products/hydrogen-chemical-economics-handbook.html> 2018.
[2] Rostrup-Nielsen JR, Rostrup-Nielsen T. Large-scale hydrogen production. CATTECH 2002;6:150–9. <https://doi.org/10.1023/A:1020163012266>.

[3] Balat M. Possible methods for hydrogen production. Energy Sources, Part A Recover Util Environ Eff 2009;31(1):39–50. <https://doi.org/10.1080/15567030701468068>.
[4] Wang Y, Zhang S. Economic assessment of selected hydrogen production methods: a review. Energy Sources B Energy Econ Plann 2017;12:1022–9. <https://doi.org/10.1080/15567249.2017.1350770>.
[5] Balzer A, Louis C, Uwe S, Fischedick M, Arnold K, Pastowski A, et al. Shell hydrogen study energy of the future? Sustainable mobility through fuel cells and H₂. <https://doi.org/10.13140/RG.2.2.31848.57604>; 2017.
[6] El-Shafie M, Kambara S, Hayakawa Y. Hydrogen production technologies overview. J Power Energy Eng 2019;7:107–54. <https://doi.org/10.4236/jpee.2019.71007>.
[7] Heo E, Kim J, Cho S. Selecting hydrogen production methods using fuzzy analytic hierarchy process with opportunities, costs, and risks. Int J Hydrogen Energy 2012;37:17655–62. <https://doi.org/10.1016/j.ijhydene.2012.09.055>.
[8] Langmi HW, McGrady GS, Newhouse R, Rönnebro E. Mg₂FeH₆-LiBH₄ and Mg₂FeH₆-6-LiNH₂ composite materials for hydrogen storage. Int J Hydrogen Energy 2012;37:6694–9. <https://doi.org/10.1016/j.ijhydene.2012.01.020>.
[9] Tozzini V, Pellegrini V. Prospects for hydrogen storage in graphene. Phys Chem Chem Phys 2013;15:80–9. <https://doi.org/10.1039/c2cp42538f>.
[10] Chilev C, Lamari FD, Ljutzkanov L, Simeonov E, Pentchev I. Hydrogen storage systems using modified sorbents for application in automobile manufacturing. Int J Hydrogen Energy 2012;37:10172–81. <https://doi.org/10.1016/j.ijhydene.2012.03.016>.
[11] Shibata T, Yamachi H, Ohmura R, Mori YH. Engineering investigation of hydrogen storage in the form of a clathrate hydrate: conceptual designs of underground hydrate-storage silos. Int J Hydrogen Energy 2012;37:7612–23. <https://doi.org/10.1016/j.ijhydene.2012.02.037>.
[12] Cheng F, Tao Z, Liang J, Chen J. Efficient hydrogen storage with the combination of lightweight Mg/MgH₂ and nanostructures. Chem Commun 2012;48:7334–43. <https://doi.org/10.1039/c2cc30740e>.
[13] Sinha P, Pandey A. An evaluative report and challenges for fermentative biohydrogen production. Int J Hydrogen Energy 2011;36:7460–78. <https://doi.org/10.1016/j.ijhydene.2011.03.077>.
[14] Poskozim PS, Principles of Modern Chemistry. (Oxtoby, david W.\$ \backslash\$mathsemicolon\$ nachtrieb, norman H.). J Chem Educ 1998;75:36. <https://doi.org/10.1021/ed075p36.1>. third ed.
[15] Grigoriev SA, Poremsky VI, Fateev VN. Pure hydrogen production by PEM electrolysis for hydrogen energy. Int J Hydrogen Energy 2006;31:171–5. <https://doi.org/10.1016/j.ijhydene.2005.04.038>.
[16] Luo X, Nam JY, Zhang F, Zhang X, Liang P, Huang X, et al. Optimization of membrane stack configuration for efficient hydrogen production in microbial reverse-electrodialysis electrolysis cells coupled with thermolytic solutions. Bioresour Technol 2013;140:399–405. <https://doi.org/10.1016/j.biortech.2013.04.097>.
[17] Zhang H, Lin G, Chen J. Evaluation and calculation on the efficiency of a water electrolysis system for hydrogen production. Int J Hydrogen Energy 2010;35:10851–8. <https://doi.org/10.1016/j.ijhydene.2010.07.088>.
[18] Elsharnoubi O, Hafez H, Nakhla G, El Naggar MH. A critical literature review on biohydrogen production by pure cultures. Int J Hydrogen Energy 2013;38:4959–66. <https://doi.org/10.1016/j.ijhydene.2013.02.032>.
[19] Guo XM, Trably E, Latrille E, Carre H, Steyer JP. Hydrogen production from agricultural waste by dark fermentation: a review. Int J Hydrogen Energy 2010;35:10660–73. <https://doi.org/10.1016/j.ijhydene.2010.03.008>.
[20] Urbaniec K, Bakker RR. Biomass residues as raw material for dark hydrogen fermentation - a review. Int J Hydrogen Energy 2015;40:3648–58. <https://doi.org/10.1016/j.ijhydene.2015.01.073>.
[21] Cui M, Yuan Z, Zhi X, Wei L, Shen J. Biohydrogen production from poplar leaves pretreated by different methods using anaerobic mixed bacteria. Int J Hydrogen Energy 2010;35:4041–7. <https://doi.org/10.1016/j.ijhydene.2010.02.035>.
[22] Monlau F, Barakat A, Trably E, Dumas C, Steyer JP, Carrère H. Lignocellulosic materials into biohydrogen and biomethane: impact of structural features and pretreatment. Crit Rev Environ Sci Technol 2013;43:260–322. <https://doi.org/10.1080/10643389.2011.604258>.
[23] Laureano-Perez L, Teymouri F, Alizadeh H, Dale BE. Understanding factors that limit enzymatic hydrolysis of biomass: characterization of pretreated corn stover. Appl Biochem Biotechnol Part A Enzyme Eng Biotechnol 2005;124:1081–100. <https://doi.org/10.1385/ABAB:124:1-3:1081>.
[24] Soares JF, Confortin TC, Toderi I, Mayer FD, Mazutti MA. Dark fermentative biohydrogen production from lignocellulosic biomass: technological challenges and future prospects. Renew Sustain Energy Rev 2020;117:109484. <https://doi.org/10.1016/j.rser.2019.109484>.
[25] Wang Z, Shao S, Zhang C, Lu D, Ma H, Ren X. Pretreatment of vinegar residue and anaerobic sludge for enhanced hydrogen and methane production in the two-stage anaerobic system. Int J Hydrogen Energy 2015;40:4494–501. <https://doi.org/10.1016/j.ijhydene.2015.02.029>.
[26] Show KY, Lee DJ, Chang JS. Bioreactor and process design for biohydrogen production. Bioresour Technol 2011;102:8524–33. <https://doi.org/10.1016/j.biortech.2011.04.055>.
[27] Asadi N, Zilouei H. Optimization of organosolv pretreatment of rice straw for enhanced biohydrogen production using *Enterobacter aerogenes*. Bioresour Technol 2017;227:335–44. <https://doi.org/10.1016/j.biortech.2016.12.073>.
[28] Moreno-Dávila IMM, Herrera-Ramírez EB, Rodríguez-Garza MM, Garza-García Y, Ríos-González LJ. Bio-hydrogen production by SSF of paper industry wastes using anaerobic biofilms: a comparison of the use of wastes with/without pretreatment.

- Int J Hydrogen Energy 2017;42:30267–73. <https://doi.org/10.1016/j.ijhydene.2017.09.054>.
- [29] Argun H, Dao S. Bio-hydrogen production from waste peach pulp by dark fermentation: effect of inoculum addition. Int J Hydrogen Energy 2017;42:2569–74. <https://doi.org/10.1016/j.ijhydene.2016.06.225>.
- [30] Torquato LDM, Pachiega R, Crespi MS, Nespeca MG, de Oliveira JE, Maintinguer SI. Potential of biohydrogen production from effluents of citrus processing industry using anaerobic bacteria from sewage sludge. Waste Manag 2017;59:181–93. <https://doi.org/10.1016/j.wasman.2016.10.047>.
- [31] Yin Y, Wang J. Gamma irradiation induced disintegration of waste activated sludge for biological hydrogen production. Radiat Phys Chem 2016. <https://doi.org/10.1016/j.radphyschem.2016.01.009>. 110–4.
- [32] Kang JH, Kim D, Lee TJ. Hydrogen production and microbial diversity in sewage sludge fermentation preceded by heat and alkaline treatment. Bioresour Technol 2012;109:239–43. <https://doi.org/10.1016/j.biortech.2012.01.048>.
- [33] O-Thong S, Hniman A, Prasertsan P, Imai T. Biohydrogen production from cassava starch processing wastewater by thermophilic mixed cultures. Int J Hydrogen Energy 2011;36:3409–16. <https://doi.org/10.1016/j.ijhydene.2010.12.053>.
- [34] Corbari SDML, Andreani CL, Torres DGB, Eng F, Gomes SD. Strategies to improve the biohydrogen production from cassava wastewater in fixed-bed reactors. Int J Hydrogen Energy 2019;44:17214–23. <https://doi.org/10.1016/j.ijhydene.2019.04.242>.
- [35] Chu CY, Wang ZF. Dairy cow solid waste hydrolysis and hydrogen/methane production by anaerobic digestion technology. Int J Hydrogen Energy 2017;42:30591–8. <https://doi.org/10.1016/j.ijhydene.2017.10.038>.
- [36] Wang S, Ma Z, Zhang T, Bao M, Su H. Optimization and modeling of biohydrogen production by mixed bacterial cultures from raw cassava starch. Front Chem Sci Eng 2017;11:100–6. <https://doi.org/10.1007/s11705-017-1617-3>.
- [37] Bao MD, Su HJ, Tan TW. Dark fermentative bio-hydrogen production: effects of substrate pre-treatment and addition of metal ions or L-cysteine. Fuel 2013;112:38–44. <https://doi.org/10.1016/j.fuel.2013.04.063>.
- [38] Nasirian N, Almami M, Minaei S, Widmann R. Development of a method for biohydrogen production from wheat straw by dark fermentation. Int J Hydrogen Energy 2011;36:411–20. <https://doi.org/10.1016/j.ijhydene.2010.09.073>.
- [39] Badiei M, Jahim JM, Anuar N, Sheikh Abdullah SR. Effect of hydraulic retention time on biohydrogen production from palm oil mill effluent in anaerobic sequencing batch reactor. Int J Hydrogen Energy 2011;36:5912–9. <https://doi.org/10.1016/j.ijhydene.2011.02.054>.
- [40] Hu B Bin, Li MY, Wang YT, Zhu MJ. High-yield biohydrogen production from non-detoxified sugarcane bagasse: fermentation strategy and mechanism. Chem Eng J 2018;335:979–87. <https://doi.org/10.1016/j.cej.2017.10.157>.
- [41] Saidi R, Liebgott PP, Gannoun H, Ben Gaidia L, Miladi B, Hamdi M, et al. Biohydrogen production from hyperthermophilic anaerobic digestion of fruit and vegetable wastes in seawater: simplification of the culture medium of Thermotoga maritima. Waste Manag 2018;71:474–84. <https://doi.org/10.1016/j.wasman.2017.09.042>.
- [42] Eker S, Sarp M. Hydrogen gas production from waste paper by dark fermentation: effects of initial substrate and biomass concentrations. Int J Hydrogen Energy 2017;42:2562–8. <https://doi.org/10.1016/j.ijhydene.2016.04.020>.
- [43] Han W, Hu Y, Li S, Li F, Tang J. Biohydrogen production in the suspended and attached microbial growth systems from waste pastry hydrolysate. Bioresour Technol 2016;218:589–94. <https://doi.org/10.1016/j.biortech.2016.07.009>.
- [44] Pan J, Zhang R, El-Mashad HM, Sun H, Ying Y. Effect of food to microorganism ratio on biohydrogen production from food waste via anaerobic fermentation. Int J Hydrogen Energy 2008;33:6968–75. <https://doi.org/10.1016/j.ijhydene.2008.07.130>.
- [45] Rorke D, Gueguim Kana EB. Biohydrogen process development on waste sorghum (Sorghum bicolor) leaves: optimization of saccharification, hydrogen production and preliminary scale up. Int J Hydrogen Energy 2016;41:12941–2. <https://doi.org/10.1016/j.ijhydene.2016.06.112>.
- [46] Sambusiti C, Bellucci M, Zabaniotou A, Beneduce L, Monlau F. Algae as promising feedstocks for fermentative biohydrogen production according to a biorefinery approach: a comprehensive review. Renew Sustain Energy Rev 2015;44:20–36. <https://doi.org/10.1016/j.rser.2014.12.013>.
- [47] Krupp M, Widmann R. Biohydrogen production by dark fermentation: experiences of continuous operation in large lab scale. Int J Hydrogen Energy 2009;34:4509–16. <https://doi.org/10.1016/j.ijhydene.2008.10.043>.
- [48] Nath K, Das D. Improvement of fermentative hydrogen production: various approaches. Appl Microbiol Biotechnol 2004;65:520–9. <https://doi.org/10.1007/s00253-004-1644-0>.
- [49] Redwood MD, Paterson-Beedle M, MacAskie LE. Integrating dark and light biohydrogen production strategies: towards the hydrogen economy. Rev Environ Sci Biotechnol 2009;8:149–85. <https://doi.org/10.1007/s11157-008-9144-9>.
- [50] Guo L, Li XM, Bo X, Yang Q, Zeng GM, Xiang Liao D, et al. Impacts of sterilization, microwave and ultrasonication pretreatment on hydrogen producing using waste sludge. Bioresour Technol 2008;99:3651–8. <https://doi.org/10.1016/j.biortech.2007.07.026>.
- [51] Wang CC, Chang CW, Chu CP, Lee DJ, Chang BV, Liao CS. Producing hydrogen from wastewater sludge by Clostridium bifermantans. J Biotechnol 2003;102:83–92. [https://doi.org/10.1016/S0168-1656\(03\)00007-5](https://doi.org/10.1016/S0168-1656(03)00007-5).
- [52] Hsieh PH, Lai YC, Chen KY, Hung CH. Explore the possible effect of TiO₂ and magnetic hematite nanoparticle addition on biohydrogen production by Clostridium pasteurianum based on gene expression measurements. Int J Hydrogen Energy 2016;41:21685–91. <https://doi.org/10.1016/j.ijhydene.2016.06.197>.
- [53] Lin R, Cheng J, Ding L, Song W, Liu M, Zhou J, et al. Enhanced dark hydrogen fermentation by addition of ferric oxide nanoparticles using Enterobacter aerogenes. Bioresour Technol 2016;207:213–9. <https://doi.org/10.1016/j.biortech.2016.02.009>.
- [54] Fonseca BC, Guazzaroni ME, Reginatto V. Fermentative production of H₂ from different concentrations of galactose by the new isolate Clostridium beijerinckii Br21. Int J Hydrogen Energy 2016;41:21109–20. <https://doi.org/10.1016/j.ijhydene.2016.09.110>.
- [55] Song ZX, Li WW, Li XH, Dai Y, Peng XX, Fan YT, et al. Isolation and characterization of a new hydrogen-producing strain Bacillus sp. FS2011. Int J Hydrogen Energy 2013;38:3206–12. <https://doi.org/10.1016/j.ijhydene.2013.01.001>.
- [56] Yin Y, Wang J. Isolation and characterization of a novel strain Clostridium butyricum INET1 for fermentative hydrogen production. Int J Hydrogen Energy 2017;42:21659–66. <https://doi.org/10.1016/j.ijhydene.2017.02.083>.
- [57] Zhao X, Xing D, Fu N, Liu B, Ren N. Hydrogen production by the newly isolated Clostridium beijerinckii RZF-1108. Bioresour Technol 2011;102:8432–6. <https://doi.org/10.1016/j.biortech.2011.02.086>.
- [58] Jiang L, Long C, Wu X, Xu H, Shao Z, Long M. Optimization of thermophilic fermentative hydrogen production by the newly isolated Caloranaerobacter azorensis H53214 from deep-sea hydrothermal vent environment. Int J Hydrogen Energy 2014;39:14154–60. <https://doi.org/10.1016/j.ijhydene.2014.05.025>.
- [59] Yin Y, Wang J. Characterization and hydrogen production performance of a novel strain Enterococcus faecium INET2 isolated from gamma irradiated sludge. Int J Hydrogen Energy 2016;41:22793–801. <https://doi.org/10.1016/j.ijhydene.2016.10.059>.
- [60] Bao M, Su H, Tan T. Biohydrogen production by dark fermentation of starch using mixed bacterial cultures of Bacillus sp and Brevumdimonas sp. Energy Fuels 2012;26:5872–8. <https://doi.org/10.1021/e300666m>.
- [61] Collet C, Adler N, Schwitzguébel JP, Péringuer P. Hydrogen production by Clostridium thermolacticum during continuous fermentation of lactose. Int J Hydrogen Energy 2004;29:1479–85. <https://doi.org/10.1016/j.ijhydene.2004.02.009>.
- [62] Rai PK, Singh SP, Asthana RK. Biohydrogen production from cheese whey wastewater in a two-step anaerobic process. Appl Biochem Biotechnol 2012;167:1540–9. <https://doi.org/10.1007/s12010-011-9488-4>.
- [63] Redwood MD, Orozco RL, Majewski AJ, Macaskie LE. Electro-extractive fermentation for efficient biohydrogen production. Bioresour Technol 2012;107:166–74. <https://doi.org/10.1016/j.biortech.2011.11.026>.
- [64] Orozco RL, Redwood MD, Leeke GA, Bahari A, Santos RCD, MacAskie LE. Hydrothermal hydrolysis of starch with CO₂ and detoxification of the hydrolysates with activated carbon for bio-hydrogen fermentation. Int J Hydrogen Energy 2012;37:6545–53. <https://doi.org/10.1016/j.ijhydene.2012.01.047>.
- [65] Eriksen NT, Nielsen TM, Iversen N. Hydrogen production in anaerobic and microaerobic Thermotoga neapolitana. Biotechnol Lett 2008;30:103–9. <https://doi.org/10.1007/s10529-007-9520-5>.
- [66] Zhu Z, Shi J, Zhou Z, Hu F, Bao J. Photo-fermentation of Rhodospirillum rubrum for hydrogen production using lignocellulose-derived organic acids. Process Biochem 2010;45. <https://doi.org/10.1016/j.procbio.2010.08.017>. 1894–8.
- [67] Zgr E, Afsar N, De Vrije T, Ycel M, Gndz U, Claassen PAM, et al. Potential use of thermophilic dark fermentation effluents in photofermentative hydrogen production by Rhodospirillum rubrum. J Clean Prod 2010;18:23–8. <https://doi.org/10.1016/j.jclepro.2010.02.020>.
- [68] Hallenbeck PC, Ghosh D. Advances in fermentative biohydrogen production: the way forward? Trends Biotechnol 2009;27:287–97. <https://doi.org/10.1016/j.tibtech.2009.02.004>.
- [69] Muhamad NS, Johan NA, Isa MH, Kutty SRM. Biohydrogen production using dark and photo fermentation: a mini review. Natl. Postgrad. Conf. - Energy Sustain. Explor. Innov. Minds, NPC 2011, IEEEE, 2011 2011. <https://doi.org/10.1109/NatPC.2011.6136349>.
- [70] Ghimire A, Frunzo L, Pirozzi F, Trably E, Escudie R, Lens PNL, et al. A review on dark fermentative biohydrogen production from organic biomass: process parameters and use of by-products. Appl Energy 2015;44:73–95. <https://doi.org/10.1016/j.apenergy.2015.01.045>.
- [71] Lee JH, Lee DG, Park J Il, Kim JY. Bio-hydrogen production from a marine brown algae and its bacterial diversity. Kor J Chem Eng 2010;27:187–92. <https://doi.org/10.1007/s11814-009-0300-x>.
- [72] Akkerman I, Janssen M, Rocha J, Wijffels RH. Photobiological hydrogen production: photochemical efficiency and bioreactor design. Int J Hydrogen Energy 2002;27:1195–208. [https://doi.org/10.1016/S0360-3199\(02\)00071-x](https://doi.org/10.1016/S0360-3199(02)00071-x).
- [73] Tao Y, Chen Y, Wu Y, He Y, Zhou Z. High hydrogen yield from a two-step process of dark- and photo-fermentation of sucrose. Int J Hydrogen Energy 2007;32:200–6. <https://doi.org/10.1016/j.ijhydene.2006.06.034>.
- [74] Yang H, Guo L, Liu F. Enhanced bio-hydrogen production from corn cob by a two-step process: dark- and photo-fermentation. Bioresour Technol 2010;101:2049–52. <https://doi.org/10.1016/j.biortech.2009.10.078>.
- [75] Chen CY, Yang MH, Yeh KL, Liu CH, Chang JS. Biohydrogen production using sequential two-stage dark and photo fermentation processes. Int J Hydrogen Energy 2008;33:4755–62. <https://doi.org/10.1016/j.ijhydene.2008.06.055>.
- [76] Lo YC, Chen CY, Lee CM, Chang JS. Photo fermentative hydrogen production using dominant components (acetate, lactate, and butyrate) in dark fermentation effluents. Int J Hydrogen Energy 2011;36:1405914068. <https://doi.org/10.1016/j.ijhydene.2011.04.148>.

- [77] Chookaew T, O-Thong S, Prasertsan P. Biohydrogen production from crude glycerol by two stage of dark and photo fermentation. *Int J Hydrogen Energy* 2015;40:7433–8. <https://doi.org/10.1016/j.ijhydene.2015.02.133>.
- [78] Avcioglu SG, Ozgur E, Eroglu I, Yucel M, Gunduz U. Biohydrogen production in an outdoor panel photobioreactor on dark fermentation effluent of molasses. *Int J Hydrogen Energy* 2011;36:11360–8. <https://doi.org/10.1016/j.ijhydene.2010.12.046>.
- [79] Tawfik A, El-Bery H, Kumari S, Bux F. Use of mixed culture bacteria for photofermentative hydrogen of dark fermentation effluent. *Bioresour Technol* 2014;168:119–26. <https://doi.org/10.1016/j.biortech.2014.03.065>.
- [80] Hwang JH, Kabra AN, Kim JR, Jeon BH. Photoheterotrophic microalgal hydrogen production using acetate- and butyrate-rich wastewater effluent. *Energy* 2014;78: 887–94. <https://doi.org/10.1016/j.energy.2014.10.086>.
- [81] Hallenbeck PC, Ghosh D. Improvements in fermentative biological hydrogen production through metabolic engineering. *J Environ Manag* 2012;95:S360–4. <https://doi.org/10.1016/j.jenvman.2010.07.021>.
- [82] Chin HL, Chen ZS, Chou CP. Fedbatch operation using *Clostridium acetobutylicum* suspension culture as biocatalyst for enhancing hydrogen production. *Biotechnol Prog* 2003;19:383–8. <https://doi.org/10.1021/bp0200604>.
- [83] Jung KW, Kim DH, Shin HS. Continuous fermentative hydrogen production from coffee drink manufacturing wastewater by applying UASB reactor. *Int J Hydrogen Energy* 2010;35:13370–8. <https://doi.org/10.1016/j.ijhydene.2009.11.120>.
- [84] Kim MS, Lee DY. Fermentative hydrogen production from tofu-processing waste and anaerobic digester sludge using microbial consortium. *Bioresour Technol* 2010;101:S48–52. <https://doi.org/10.1016/j.biortech.2009.03.040>.
- [85] Guo L, Zhao J, She Z, Lu M, Zong Y. Effect of S-TE (solubilization by thermophilic enzyme) digestion conditions on hydrogen production from waste sludge. *Bioresour Technol* 2012;117:368–72. <https://doi.org/10.1016/j.biortech.2012.04.010>.
- [86] Oh YK, Kim HJ, Park S, Kim MS, Ryu DDY. Metabolic-flux analysis of hydrogen production pathway in *Citrobacter amalonaticus* Y19. *Int J Hydrogen Energy* 2008;33:1471–82. <https://doi.org/10.1016/j.ijhydene.2007.09.032>.
- [87] Kim M, Yang Y, Morikawa-Sakura MS, Wang Q, Lee MV, Lee DY, et al. Hydrogen production by anaerobic co-digestion of rice straw and sewage sludge. *Int J Hydrogen Energy* 2012;37:3142–9. <https://doi.org/10.1016/j.ijhydene.2011.10.116>.
- [88] Alvarado-Cuevas ZD, Acevedo LGO, Salas JTO, De León-Rodríguez A. Nitrogen sources impact hydrogen production by *Escherichia coli* using cheese whey as substrate. *N Biotech* 2013;30:585–90. <https://doi.org/10.1016/j.nbt.2013.03.002>.
- [89] Sagnak R, Kargi F, Kapdan IK. Bio-hydrogen production from acid hydrolyzed waste ground wheat by dark fermentation. *Int J Hydrogen Energy* 2011;36: 12803–9. <https://doi.org/10.1016/j.ijhydene.2011.07.076>.
- [90] Kumar N, Das D. Continuous hydrogen production by immobilized *Enterobacter cloacae* IIT-BT 08 using lignocellulosic materials as solid matrices. *Enzym Microb Technol* 2001;29:280–7. [https://doi.org/10.1016/S0141-0229\(01\)00394-5](https://doi.org/10.1016/S0141-0229(01)00394-5).
- [91] Ueno Y, Haruta S, Ishii M, Igarashi Y. Characterization of a microorganism isolated from the effluent of hydrogen fermentation by microflora. *J Biosci Bioeng* 2001;92:397–400. [https://doi.org/10.1016/S1389-1723\(01\)80247-4](https://doi.org/10.1016/S1389-1723(01)80247-4).
- [92] Lo YC, Chen WM, Hung CH, Chen S Der, Chang JS. Dark H₂ fermentation from sucrose and xylose using H₂-producing indigenous bacteria: feasibility and kinetic studies. *Water Res* 2008;42:827–42. <https://doi.org/10.1016/j.watres.2007.08.023>.
- [93] Akutsu Y, Lee DY, Chi YZ, Li YY, Harada H, Yu HQ. Thermophilic fermentative hydrogen production from starch-wastewater with bio-granules. *Int J Hydrogen Energy* 2009;34:5061–71. <https://doi.org/10.1016/j.ijhydene.2009.04.024>.
- [94] Ozmihiç S, Kargi F. Bio-hydrogen production by photo-fermentation of dark fermentation effluent with intermittent feeding and effluent removal. *Int J Hydrogen Energy* 2010;35:6674–80. <https://doi.org/10.1016/j.ijhydene.2010.04.090>.
- [95] Yokoi H, Mori S, Hirose J, Hayashi S, Takasaki Y. H₂ production from starch by a mixed culture of *Clostridium butyricum* and *Rhodobacter* sp. M-19. *Biotechnol Lett* 1998;20:895–9. <https://doi.org/10.1023/A:1005327912678>.
- [96] Liu BF, Ren NQ, Tang J, Ding J, Liu WZ, Xu JF, et al. Bio-hydrogen production by mixed culture of photo- and dark-fermentation bacteria. *Int J Hydrogen Energy* 2010;35:2858–62. <https://doi.org/10.1016/j.ijhydene.2009.05.005>.
- [97] Kapdan IK, Kargi F, Oztekin R, Argun H. Bio-hydrogen production from acid hydrolyzed wheat starch by photo-fermentation using different *Rhodobacter* sp. *Int J Hydrogen Energy* 2009;34:2201–7. <https://doi.org/10.1016/j.ijhydene.2009.01.017>.
- [98] Chen S Der, Lee KS, Lo YC, Chen WM, Wu JF, Lin CY, et al. Batch and continuous biohydrogen production from starch hydrolysate by *Clostridium* species. *Int J Hydrogen Energy* 2008;33:1803–12. <https://doi.org/10.1016/j.ijhydene.2008.01.028>.
- [99] Argun H, Kargi F, Kapdan IK. Microbial culture selection for bio-hydrogen production from waste ground wheat by dark fermentation. *Int J Hydrogen Energy* 2009;34:2195–200. <https://doi.org/10.1016/j.ijhydene.2008.12.066>.
- [100] Argun H, Kargi F. Bio-hydrogen production from ground wheat starch by continuous combined fermentation using annular-hybrid bioreactor. *Renew Energy* 2010;35:6170–8. <https://doi.org/10.1016/j.renene.2010.03.132>.
- [101] Arooj MF, Han SK, Kim SH, Kim DH, Shin HS. Continuous biohydrogen production in a CSTR using starch as a substrate. *Int J Hydrogen Energy* 2008;33: 3289–94. <https://doi.org/10.1016/j.ijhydene.2008.04.022>.
- [102] Micro-propagation of disease resistant cassava variety in Rwanda. Rwanda J 2011;24. <https://www.ajol.info/index.php/rj/article/view/76>.
- [103] Bao Meidan, Su Haijia, Tan T. Biohydrogen production by dark fermentation of starch using mixed bacterial cultures of *Bacillus* sp and *Brevumdimonas* sp. *Energy Fuels* 2012;26:5872–8. <https://doi.org/10.1021/ef300666m>.
- [104] Chen S Der, Sheu DS, Chen WM, Lo YC, Huang TI, Lin CY, et al. Dark hydrogen fermentation from hydrolyzed starch treated with recombinant amylase originating from *Caldimonas taiwanensis* On1. *Biotechnol Prog* 2007;23: 1312–20. <https://doi.org/10.1021/bp070187z>.
- [105] Lin CY, Cheng CH. Fermentative hydrogen production from xylose using anaerobic mixed microflora. *Int J Hydrogen Energy* 2006;31:832–40. <https://doi.org/10.1016/j.ijhydene.2005.08.010>.
- [106] Zhang ML, Fan YT, Xing Y, Pan CM, Zhang GS, Lay JJ. Enhanced biohydrogen production from cornstalk wastes with acidification pretreatment by mixed anaerobic cultures. *Biomass Bioenergy* 2007;31:250–4. <https://doi.org/10.1016/j.biombioe.2006.08.004>.
- [107] Evvyernie D, Morimoto K, Karita S, Kimura T, Sakka K, Ohmiya K. Conversion of chitinous wastes to hydrogen gas by *Clostridium paraputificum* M-21. *J Biosci Bioeng* 2001;91:339–43. [https://doi.org/10.1016/S1389-1723\(01\)80148-1](https://doi.org/10.1016/S1389-1723(01)80148-1).
- [108] Fan YT, Zhang GS, Guo XY, Xing Y, Fan MH. Biohydrogen-production from beer lees biomass by cow dung compost. *Biomass Bioenergy* 2006;30:493–6. <https://doi.org/10.1016/j.biombioe.2005.10.009>.
- [109] Levin DB, Islam R, Cicek N, Sparling R. Hydrogen production by *Clostridium thermocellum* 27405 from cellulosic biomass substrates. *Int J Hydrogen Energy* 2006;31:1496–503. <https://doi.org/10.1016/j.ijhydene.2006.06.015>.
- [110] Shin HS, Youn JH, Kim SH. Hydrogen production from food waste in anaerobic mesophilic and thermophilic acidogenesis. *Int J Hydrogen Energy* 2004;29: 1355–63. <https://doi.org/10.1016/j.ijhydene.2003.09.011>.
- [111] Tanisho S, Ishiwata Y. Continuous hydrogen production from molasses by fermentation using urethane foam as a support of flocks. *Int J Hydrogen Energy* 1995;20:541–5. [https://doi.org/10.1016/0360-3199\(94\)00101-5](https://doi.org/10.1016/0360-3199(94)00101-5).
- [112] Venkata Mohan S, Lalit Babu V, Sarma PN. Effect of various pretreatment methods on anaerobic mixed microflora to enhance biohydrogen production utilizing dairy wastewater as substrate. *Bioresour Technol* 2008;99:59–67. <https://doi.org/10.1016/j.biortech.2006.12.004>.
- [113] Vignais PM, Billoud B. Occurrence, classification, and biological function of hydrogenases: an overview. *Chem Rev* 2007;107:4206–72. <https://doi.org/10.1021/cr050196r>.
- [114] Vignais PM. Hydrogenases and H⁺-reduction in primary energy conservation. *Bioenergetics*. Springer Berlin Heidelberg; 2008. p. 223–52. https://doi.org/10.1007/400_2006_027.
- [115] Wang J, Wan W. Effect of temperature on fermentative hydrogen production by mixed cultures. *Int J Hydrogen Energy* 2008;33:5392–7. <https://doi.org/10.1016/j.ijhydene.2008.07.010>.
- [116] Li C, Fang HHP. Inhibition of heavy metals on fermentative hydrogen production by granular sludge. *Chemosphere* 2007;67:668–73. <https://doi.org/10.1016/j.chemosphere.2006.11.005>.
- [117] Karadag D, Puhakka JA. Enhancement of anaerobic hydrogen production by iron and nickel. *Int J Hydrogen Energy* 2010;35:8554–60. <https://doi.org/10.1016/j.ijhydene.2010.04.174>.
- [118] Hallenbeck PC. Fermentative hydrogen production: principles, progress, and prognosis. *Int J Hydrogen Energy* 2009;34:7379–89. <https://doi.org/10.1016/j.ijhydene.2008.12.080>.
- [119] Bisaillon A, Turcot J, Hallenbeck PC. The effect of nutrient limitation on hydrogen production by batch cultures of *Escherichia coli*. *Int J Hydrogen Energy* 2006;31: 1504–8. <https://doi.org/10.1016/j.ijhydene.2006.06.016>.
- [120] Maeda T, Sanchez-Torres V, Wood TK. Enhanced hydrogen production from glucose by metabolically engineered *Escherichia coli*. *Appl Microbiol Biotechnol* 2007;77:879–90. <https://doi.org/10.1007/s00253-007-1217-0>.
- [121] Yoshida A, Nishimura T, Kawaguchi H, Inui M, Yukawa H. Enhanced hydrogen production from glucose using *ldh-* and *frd-*inactivated *Escherichia coli* strains. *Appl Microbiol Biotechnol* 2006;73:67–72. <https://doi.org/10.1007/s00253-006-0456-9>.
- [122] King PW, Posewitz MC, Ghirardi ML, Seibert M. Functional studies of [FeFe] hydrogenase maturation in an *Escherichia coli* biosynthetic system. *J Bacteriol* 2006;188:2163–72. <https://doi.org/10.1128/JB.188.6.2163-2172.2006>.
- [123] Maeda T, Sanchez-Torres V, Wood TK. Protein engineering of hydrogenase 3 to enhance hydrogen production. *Appl Microbiol Biotechnol* 2008;79:77–86. <https://doi.org/10.1007/s00253-008-1416-3>.
- [124] Poladyan A, Trchounian K, Vassilian A, Trchounian A. Hydrogen production by *Escherichia coli* using brewery waste: optimal pretreatment of waste and role of different hydrogenases. *Renew Energy* 2018;115:931–6. <https://doi.org/10.1016/j.renene.2017.09.022>.
- [125] Cha M, Chung D, Elkins JG, Guss AM, Westpheling J. Metabolic engineering of *Caldicellulosiruptor bescii* yields increased hydrogen production from lignocellulosic biomass. *Biotechnol Biofuels* 2013;6:85. <https://doi.org/10.1186/1754-6834-6-85>.
- [126] Lee SY, Lee HJ, Park JM, Lee JH, Park JS, Shin HS, et al. Bacterial hydrogen production in recombinant *Escherichia coli* harboring a HupSL hydrogenase isolated from *Rhodobacter sphaeroides* under anaerobic dark culture. *Int J Hydrogen Energy* 2010;35:1112–6. <https://doi.org/10.1016/j.ijhydene.2009.11.068>.
- [127] Wang J, Yu W, Xu L, Wang S, Yan Y. Effects of increasing the NAD(H) pool on hydrogen production and metabolic flux distribution in *Enterobacter aerogenes* mutants. *Int J Hydrogen Energy* 2013;38:13204–15. <https://doi.org/10.1016/j.ijhydene.2013.07.121>.

- [128] Bai L, Wu X, Jiang L, Liu J, Long M. Hydrogen production by over-expression of hydrogenase subunit in oxygen-tolerant *Klebsiella oxytoca* HP1. *Int J Hydrogen Energy* 2012;37:13227–33. <https://doi.org/10.1016/j.ijhydene.2012.03.048>.
- [129] Jo JH, Jeon CO, Lee SY, Lee DS, Park JM. Molecular characterization and homologous overexpression of [FeFe]-hydrogenase in *Clostridium tyrobutyricum* JM1. *Int J Hydrogen Energy* 2010;35:1065–73. <https://doi.org/10.1016/j.ijhydene.2009.11.102>.
- [130] Sarma S, Ortega D, Minton NP, Dubey VK, Moholkar VS. Homologous overexpression of hydrogenase and glycerol dehydrogenase in *Clostridium pasteurianum* to enhance hydrogen production from crude glycerol. *Bioresour Technol* 2019;284:168–77. <https://doi.org/10.1016/j.biortech.2019.03.074>.
- [131] Wang R, Zong W, Qian C, Wei Y, Yu R, Zhou Z. Isolation of *Clostridium perfringens* strain W11 and optimization of its biohydrogen production by genetic modification. *Int J Hydrogen Energy* 2011;36:12159–67. <https://doi.org/10.1016/j.ijhydene.2011.06.105>.
- [132] Hallenbeck PC, Benemann JR. Biological hydrogen production; Fundamentals and limiting processes. *Int J Hydrogen Energy* 2002;27:1185–93. [https://doi.org/10.1016/S0360-3199\(02\)00131-3](https://doi.org/10.1016/S0360-3199(02)00131-3).
- [133] Nath K, Muthukumar M, Kumar A, Das D. Kinetics of two-stage fermentation process for the production of hydrogen. *Int J Hydrogen Energy* 2008;33:1195–203. <https://doi.org/10.1016/j.ijhydene.2007.12.011>.
- [134] Gavala HN, Skiadas IV, Ahring BK. Biological hydrogen production in suspended and attached growth anaerobic reactor systems. *Int J Hydrogen Energy* 2006;31:1164–75. <https://doi.org/10.1016/j.ijhydene.2005.09.009>.
- [135] Li D, Chen H. Biological hydrogen production from steam-exploded straw by simultaneous saccharification and fermentation. *Int J Hydrogen Energy* 2007;32:1742–8. <https://doi.org/10.1016/j.ijhydene.2006.12.011>.
- [136] Fascetti E, D'Addario E, Todini O, Robertiello A. Photosynthetic hydrogen evolution with volatile organic acids derived from the fermentation of source selected municipal solid wastes. *Int J Hydrogen Energy* 1998;23:753–60. [https://doi.org/10.1016/S0360-3199\(97\)00123-7](https://doi.org/10.1016/S0360-3199(97)00123-7).
- [137] Fang HHP, Li C, Zhang T. Acidophilic biohydrogen production from rice slurry. *Int J Hydrogen Energy* 2006;31:683–92. <https://doi.org/10.1016/j.ijhydene.2005.07.005>.
- [138] Horiuchi JI, Shimizu T, Tada K, Kanno T, Kobayashi M. Selective production of organic acids in anaerobic acid reactor by pH control. *Bioresour Technol* 2002;82:209–13. [https://doi.org/10.1016/S0960-8524\(01\)00195-X](https://doi.org/10.1016/S0960-8524(01)00195-X).
- [139] Lin CY, Lay CH. A nutrient formulation for fermentative hydrogen production using anaerobic sewage sludge microflora. *Int J Hydrogen Energy* 2005;30:285–92. <https://doi.org/10.1016/j.ijhydene.2004.03.002>.
- [140] Sasaki K. *Hydrogen and 5-aminolevulinic acid production by photosynthetic bacteria*. Biohydrogen: Springer; 1998. p. 133–42.
- [141] Uyar B, Eroglu I, Yücel M, Gündüz U. Photofermentative hydrogen production from volatile fatty acids present in dark fermentation effluents. *Int J Hydrogen Energy* 2009;34:4517–23. <https://doi.org/10.1016/j.ijhydene.2008.07.057>.
- [142] Barbosa MJ, Rocha JMS, Tramer J, Wijffels RH. Acetate as a carbon source for hydrogen production by photosynthetic bacteria. *J Biotechnol* 2001;85:25–33. [https://doi.org/10.1016/S0168-1656\(00\)00368-0](https://doi.org/10.1016/S0168-1656(00)00368-0).
- [143] Lo YC, Su YC, Chen CY, Chen WM, Lee KS, Chang JS. Biohydrogen production from cellulosic hydrolysate produced via temperature-shift-enhanced bacterial cellulose hydrolysis. *Bioresour Technol* 2009;100:5802–7. <https://doi.org/10.1016/j.biortech.2009.06.066>.
- [144] Zhang C, Kang X, Liang N, Abdullah A. Improvement of biohydrogen production from dark fermentation by cocultures and activated carbon immobilization. *Energy Fuels* 2017;31:12217–22. <https://doi.org/10.1021/acs.energyfuels.7b02035>.
- [145] Cheng J, Ding L, Lin R, Yue L, Liu J, Zhou J, et al. Fermentative biohydrogen and biomethane co-production from mixture of food waste and sewage sludge: effects of physicochemical properties and mix ratios on fermentation performance. *Appl Energy* 2016;184:1–8. <https://doi.org/10.1016/j.apenergy.2016.10.003>.
- [146] Dictor MC, Joulian C, Touzé S, Ignatiadis I, Guyonnet D. Electro-stimulated biological production of hydrogen from municipal solid waste. *Int J Hydrogen Energy* 2010;35:10682–92. <https://doi.org/10.1016/j.ijhydene.2010.03.053>.
- [147] Sircar S, Golden TC. Purification of hydrogen by pressure swing adsorption. *Separ Sci Technol* 2000;35:667–87. <https://doi.org/10.1081/SS-100100183>.
- [148] Cheng YS, Peña MA, Fierro JL, Hui DCW, Yeung KL. Performance of alumina, zeolite, palladium, Pd-Ag alloy membranes for hydrogen separation from Towngas mixture. *J Membr Sci* 2002;204:329–40. [https://doi.org/10.1016/S0376-7388\(02\)00059-5](https://doi.org/10.1016/S0376-7388(02)00059-5).
- [149] Kluiters SCA. Status review on membrane systems for hydrogen separation. 2004. <https://publicaties.ecn.nl/PdfFetch.aspx?nr=ECN-C-04-102>.
- [150] Lee D. Studies on hydrogen selective silica membranes and the catalytic reforming of CH₄ with CO₂ in a membrane reactor. Virginia Tech 2003. <https://techworks.lib.vt.edu/handle/10919/28543>.
- [151] Roa F, Way JD. Influence of alloy composition and membrane fabrication on the pressure dependence of the hydrogen flux of palladium-copper membranes. *Ind Eng Chem Res* 2003;42:5827–35. <https://doi.org/10.1021/ie030426x>.
- [152] Wang LJ, Hong FCN. Carbon-based molecular sieve membranes for gas separation by inductively-coupled-plasma chemical vapor deposition. *Microporous Mesoporous Mater* 2005;77:167–74. <https://doi.org/10.1016/j.micromeso.2004.09.001>.
- [153] Parsons G. Capital and operating cost of hydrogen from coal gasification. *New Dir. Youth Dev.*, Wiley; 2003. <https://doi.org/10.1002/yd.370>.
- [154] Sathyaprakasan P, Kannan G. Economics of bio-hydrogen production. *Int J Environ Sustain Dev* 2015;6(5):352–6. <https://doi.org/10.7763/ijesd.2015.v6.617>.
- [155] Elbeshbishy E, Dhar BR, Nakhla G, Lee HS. A critical review on inhibition of dark biohydrogen fermentation. *Renew Sustain Energy Rev* 2017;79:656–68. <https://doi.org/10.1016/j.rser.2017.05.075>.
- [156] Arimi MM, Knodel J, Kiprop A, Namango SS, Zhang Y, Geißen SU. Strategies for improvement of biohydrogen production from organic-rich wastewater: a review. *Biomass Bioenergy* 2015;75:101–18. <https://doi.org/10.1016/j.biombioe.2015.02.011>.
- [157] Trchounian K, Sawers RG, Trchounian A. Improving biohydrogen productivity by microbial dark- and photo-fermentations: novel data and future approaches. *Renew Sustain Energy Rev* 2017;80:1201–16. <https://doi.org/10.1016/j.rser.2017.05.149>.
- [158] Acar C, Dincer I. Comparative assessment of hydrogen production methods from renewable and non-renewable sources. *Int J Hydrogen Energy* 2014;39:1–12. <https://doi.org/10.1016/j.ijhydene.2013.10.060>.
- [159] Dincer I, Acar C. Review and evaluation of hydrogen production methods for better sustainability. *Int J Hydrogen Energy* 2015;40:11094–111. <https://doi.org/10.1016/j.ijhydene.2014.12.035>.
- [160] Kalamaras CM, Efstathiou AM. Hydrogen production technologies: current state and future developments. *Conf Pap Energy* 2013;2013:1–9. <https://doi.org/10.1155/2013/690627>.
- [161] Penner SS. Steps toward the hydrogen economy. *Energy* 2006;31:33–43. <https://doi.org/10.1016/j.energy.2004.04.060>.
- [162] Rutkowski M. Current. Hydrogen from SMR natural gas with CO₂ capture and sequestration. 2005 [WWW Document], <http://www.Hydrog.Energy.Gov/H2a.Prod.Stud.Html>.
- [163] Kreutz T, Williams R, Socolow R, Chiesa P, Lozza G. Production of hydrogen and electricity from coal with CO₂ capture. *Greenh. Gas control technol. - 6th int. Conf.* Elsevier; 2003. p. 141–7. <https://doi.org/10.1016/B978-008044276-1/50023-4>.
- [164] Petri J, Marker T. Production of diesel fuel from biorenewable feedstocks. 2006.
- [165] Richards M, Shenoy A. H₂-MHR pre-conceptual design summary for hydrogen production. *Nucl Eng Technol* 2007;39:1–8. <https://doi.org/10.5516/NET.2007.39.1.001>.
- [166] Schultz KR. Use of the modular helium reactor for hydrogen production. 2003.
- [167] Bockris JOM, Veziroglu TN. Estimates of the price of hydrogen as a medium for wind and solar sources. *Int J Hydrogen Energy* 2007;32:1605–10. <https://doi.org/10.1016/j.ijhydene.2007.04.037>.
- [168] Levene JI, Mann MK, Margolis RM, Milbrandt A. An analysis of hydrogen production from renewable electricity sources. *Sol Energy* 2007;81:773–80. <https://doi.org/10.1016/j.solener.2006.10.005>.
- [169] Glatzmaier GC. Measurement of hydrogen purge rates in Parabolic Trough receiver tubes. 2010. <https://www.osti.gov/biblio/991562>.
- [170] Kolb GJ, Diver RB, Siegel N. Central-station solar hydrogen power plant. *J Sol Energy Eng* 2007;129:179–83. <https://doi.org/10.1115/1.2710246>.
- [171] Mann LC, Corbett TJ, Liu Q, Prasad R. Hydrogen generation system. 2004.
- [172] Padro CEG, Putsche V. Survey of the economics of hydrogen technologies. 1999.
- [173] Bartels JR, Pate MB, Olson NK. An economic survey of hydrogen production from conventional and alternative energy sources. *Int J Hydrogen Energy* 2010;35:8371–84. <https://doi.org/10.1016/j.ijhydene.2010.04.035>.
- [174] Demirbas MF. Hydrogen from various biomass species via pyrolysis and steam gasification processes. *Energy Sources, Part A Recover Util Environ Eff* 2006;28:245–52. <https://doi.org/10.1080/009083190890003>.