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Techno-economic and environmental impact assessment of hydrogen production processes using bio-waste as renewable energy resource

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Abstract

There is a wide spectrum of biological wastes, from which H_2 production can generate clean energy while minimizing environmental degradation. This study aims to conduct techno-economic and environmental impact assessment of major hydrogen production processes such as dark, photo and solid-state fermentation, microbial electrolysis cell (MEC), gasification, pyrolysis and plasma. From the technological point of view, the dark fermentation has shown better performance in comparison to the other processes. However, the hybrid dark fermentation with photo-fermentation and MEC has shown higher performances with around 1 L H_2/g organic waste. Regarding the economic aspect, the cheapest H_2 production belongs to gasification and fermentation with approximately 2 US$/g and 2.3 US$/g followed by plasma (2.4 US$/g), pyrolysis (2.6 US$/g), MEC (2.8 US$/g), and photo-fermentation (3.5 US$/g). Regarding the potential environmental impact, the fermentation process showed the lowest greenhouse gas emission with 15 kg CO_2-eq/kg hydrogen followed by gasification, MEC and plasma. Regarding the potential commercial applications, gasification is the most mature with the highest possible technology readiness at level 9.

Keywords: Hydrogen; Techno-economic analysis; Life cycle analysis; Fermentation; Microbial electrolysis cell; Gasification

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Highlights

- Potential processes for H_2 production from bio-wastes were critically reviewed.
- Techno-economic, efficiency and life cycle analyses of the processes were conducted.
- Hybrid processes showed cheaper and cleaner H_2 production than single process.
- Dark fermentation with microbial electrolysis cell demonstrated best performance.

Abbreviations

acetyl-CoA	acetyl coenzyme A
AD	anaerobic digestion
ANFIS	adaptive network-based fuzzy inference system
ANN	artificial neural network
ATP	adenosine triphosphate
CFD	computational fluid dynamics
COD	chemical oxygen demand
DAEM	distributed activation energy model
EF	entrained flow
FB	fluidized bed
GHG	greenhouse gases
HCs	hydrocarbons
HRT	hydraulic retention time
LCA	life cycle analysis
LCOH	levelized cost of hydrogen
MEC	microbial electrolysis cell
MSW	municipal solid waste
OLR	organic loading rate

PAHs	polycyclic aromatic hydrocarbons
PM	particulate matter
PMW	paper mill waste
SSF	solid-state fermentation
VFAs	volatile fatty acids
VS	volatile solid
TEA	techno-economic analysis
TRL	technology readiness level

1. Introduction

With the rapid urbanization, industrialization and population growth, the global energy requirement is estimated to increase by 56% from 553 quadrillion kJ to 855 quadrillion kJ during 2010-2040 [1, 2]. As the dominant energy sources, fossil fuels such as coal and petroleum are regarded as nonrenewable energy . In addition, the combustion of fossil fuels in power generation and transport emits various pollutants including greenhouse gases (GHG), carbon monoxide, nitrogen oxides, particulate matter (PM) and organic pollutants such as polycyclic aromatic hydrocarbons (PAHs) into the atmosphere [3-5]. The global warming from GHG emissions has caused different types of detrimental effects on human wellbeing in all continents, e.g. undernutrition and mental health effects from droughts and floods in South Africa, Ethiopia, Bangladesh and China along with respiratory and cardiovascular impacts of record heatwaves and wildfires in western Europe, western North America and Australia [5]. Climate change has become a threat for many foundations of wellbeing and human health over a long period of time [6, 7]. The emitted pollutants are not only toxic and even carcinogenic, but also can induce secondary organic aerosols with human health implications [7, 8]. Such adverse effects are most felt in urban areas with a high density of human population, as it is estimated that vehicle emissions are responsible for an estimated 385000 premature deaths and US$1 trillion of health damage globally in 2015 [9].

Currently, approximately 64% of the gross inland consumption of renewable energy in the European Union belongs to bioenergy [10]. It is expected that renewable energy production will contribute approximately 51% of the total energy requirements globally by 2040, and become the dominating energy source in the next decade [11]. In addition, freshwater shortage is regarded as another severe problem of the world today [1, 12]. Moreover, solid waste and wastewater are considered as the most severe environmental problems today [12-15], yet they can provide valuable sources of biomasses for the recovery of energy [15]. There is a wide range of technologies to manage each of these challenges separately, e.g. by applying composting and vermicomposting processes for waste disposal [14, 16], advanced oxidation processes [17-19] for water and wastewater treatment, and energy generation from renewable energy resources like wind and wave [20]. However, the development of processes by which water and energy shortages together with environmental and health problems of wastes such as municipal solid waste (MSW) can be simultaneously addressed is exciting and urgently needed [21].

Hydrogen is a very interesting energy carrier with an energy yield of 122 kJ/g that is 2.75 times more than the fossil fuels. Hydrogen as a clean energy is free of CO_2 and any toxic emissions during combustion, with water as the final product. In fact, the application of hydrogen as a fuel meets the zero-emission target which is now globally pursued. Hydrogen can be produced from biomass and renewable sources, and more attentions have been attracted towards the generation of hydrogen from wastes and wastewater [7, 22]. There are various technologies for the production of hydrogen from wastes and wastewater, i.e. photo [22], dark and solid-state fermentation (SSF) [23], microbial electrolysis cell (MEC) [1], pyrolysis [24], gasification [25] and plasma [26]. These processes have been studied for different types of solid and liquid wastes; however, there is still a knowledge gap regarding which process is the best option for hydrogen production and treatment efficiency from the full techno-economic analysis (TEA) and environmental impact analysis. Table 1 compares this review article and other related published review papers. Although other papers have examined different aspects of H_2 production in various processes, the emerging processes for H_2 production, e.g. SSF, MEC and plasma were less studied in techno-economic and environmental impact analysis. Furthermore, current information about the TEA and environmental aspects in more mature processes like pyrolysis and gasification is insufficient to allow the selection of the best process for H_2 production from different types of bio-wastes.

Table 1.

Comparison of this study with other review articles on hydrogen production as renewable energy.

Process	Evaluation	Reference							
		[27]	[28]	[29]	[30]	[31]	[32]	[33]	This study
Dark fermentation	Efficiency analysis	×	√	√	×	×	×	×	√
	TEA	×	×	×	×	×	√	×	√
	LCA	×	×	×	×	×	×	×	√
	Bio-waste	×	√	√	×	×	√	×	√
Photo fermentation	Efficiency analysis	×	×	×	×	×	×	×	√
	TEA	×	×	×	×	×	√	×	√
	LCA	×	×	×	×	×	×	×	√
	Bio-waste	×	×	×	×	×	√	×	√
SSF	Efficiency analysis	×	×	×	×	×	×	×	√
	TEA	×	×	×	×	×	×	×	√
	LCA	×	×	×	×	×	×	×	√
	Bio-waste	×	×	×	×	×	×	×	√
MEC	Efficiency analysis	×	×	×	×	×	×	×	√
	TEA	×	×	×	×	×	×	×	√
	LCA	×	×	×	×	×	×	×	√
	Bio-waste	×	×	×	×	×	×	×	√
Pyrolysis	Efficiency analysis	×	×	×	×	×	√	√	√

	TEA	×	×	×	×	×	√	×	√
	LCA	×	×	×	×	×	×	×	√
	Bio-waste	×	×	×	×	×	√	√	√
Gasification	Efficiency analysis	×	×	×	√	×	√	√	√
	TEA	×	×	×	√	×	√	√	√
	LCA	×	×	×	×	×	×	√	√
	Bio-waste	√	×	×	√	×	√	√	√
Plasma	Efficiency analysis	×	×	×	×	×	×	√	√
	TEA	×	×	×	×	×	×	√	√
	LCA	×	×	×	×	×	×	×	√
	Bio-waste	×	×	×	×	×	×	√	√
Other H_2 production processes studied		√	×	×	√	√	√	√	√
Comprehensive appraisal of all processes		×	×	×	×	×	×	×	√

This study aims to address the mechanisms, technical and operating conditions, economic and environmental aspects of common and emerging hydrogen production processes from wastes and wastewater, including photo fermentation, dark fermentation, solid fermentation, MEC, pyrolysis, gasification, and plasma processes. Based on the advantages, disadvantages and capabilities of these processes, the best process will be recommended for further research and commercial exploitation.

2. Technical analysis of hydrogen production processes from wastes

2.1. Dark, photo and solid-state fermentation

Anaerobic biological processes such as anaerobic digestion (AD), which normally consist of four different stages including hydrolysis, acidogenesis, acetogenesis and methanogenesis, are regarded as one of the most effective processes for both treatment of the wastes and energy production [34]. Acidogenic fermentation, which is conducted using a consortium of microorganisms and includes only first three stages of the anaerobic biological process, plays a vital role during this process by linking the hydrolysis and methanogenesis stages [34, 35]. In order to produce acidogenic products, syntrophic activities of the microorganisms in anaerobic processes play an important role, by syntrophically degrading the organic matter into hydrogen and other acidogenic phase products. Since a wide spectrum of the microorganisms are used and there are different pathways in this process, interspecies transfer of mass and electron is one of the key mechanisms for hydrogen and fatty acid production in such communities [34]. The mechanisms of the organic matter degradation in dark fermentation process as well as H_2 production are demonstrated in Fig. 1.

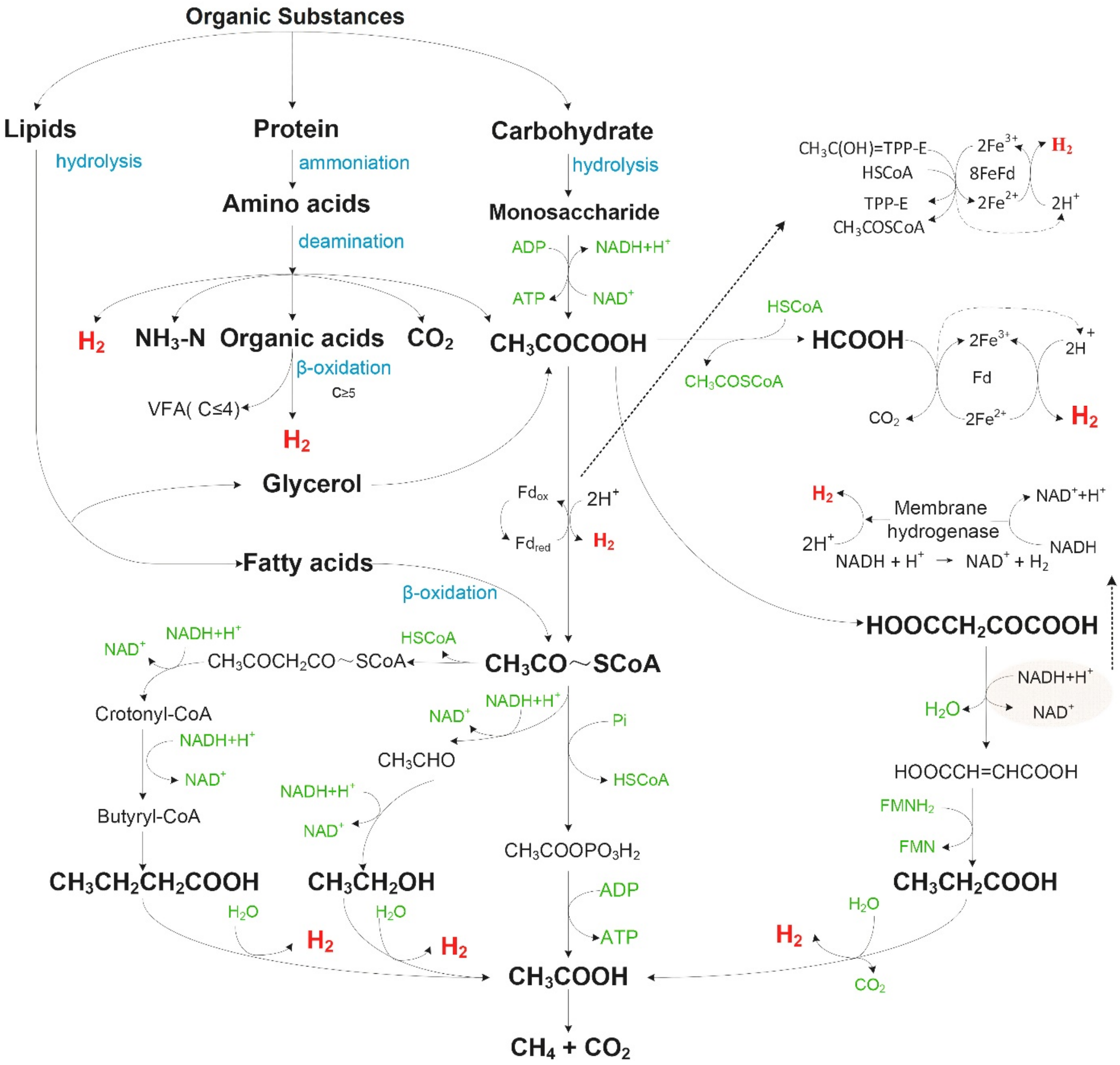


Fig. 1. Hydrogen production pathways by fermentation process from organic substances. Reproduced with permission from reference [36]. Copyright © 2021 Fu Q. et al, Elsevier. (License No. 5163900883526)

As observed in Fig. 1, different types of organic matter can potentially be converted into H_2 by fermentation. However, the conversion of the different types of organic matter can be carried out through different pathways with different energy outputs. The shortest pathways to produce H_2 from organic matter are *via* β-oxidation of organic acids, and deamination of the amino acids. The other H_2 production pathway, which is dominant with *Clostridium* spp., is the decarboxylation of pyruvate through ferredoxin enzyme. During the glycolysis of amino acids and carbohydrates, pyruvate is produced and degraded to acetyl-CoA, the generated electrons over this process could react with protons and generate H_2. Facultative anaerobes dominantly produce H_2 through format cleavage as well [36]. In addition, the required adenosine triphosphate (ATP) and energy obtained from proton gradient process are also indicated in Fig. 1.

After the dark fermentation process, there is a great proportion of volatile fatty acids (VFAs) in the system, which can be used by photosynthetic bacteria to recover more hydrogen from organic matter. Purple non-sulfur bacteria, which are able to gain electrons from VFAs to generate H_2, are regarded as the most dominant photosynthetic bacteria investigated in photo-fermentation processes. In these processes, ubiquinone transports the produced electrons from the oxidation of organic matter to the photosystem. Subsequently, the light energizes the transported electrons, which are cycled in electron transport chain of photosynthetic system resulting in more proton gradients. Finally, oxidoreductase transfers the electrons to ferredoxin which is applied to generate H_2 by nitrogenase. This process is considered as photo-fermentation process, which has been suggested to combine with dark fermentation to produce more H_2 [36].

SSF process operates in the same way as the dark fermentation process with almost zero free water [37]. Since the proportion of the biomass in SSF is higher than that of the submerged fermentation, the productivity of SSF is enhanced. Therefore, SSF is considered as more economic from the aspect of capital and operating costs. The main challenges of SSF are the determination of the microbial biomass, product recovery and scale-up operation [38].

These three processes have been widely applied for H_2 production from different types of wastes. However, these processes have shown various performances under different operation conditions. Table 2 summarizes the operating conditions as well as the performance of these processes in H_2 production and waste treatment efficiency.

As shown in Tables 2 and 3, the proportions of the H_2 produced by the integrated dark and photo fermentation processes are higher than separate dark and photo fermentations. In addition, single dark fermentation has demonstrated better performance in the production of H_2 from wastes compared with single photo fermentation processes. Apart from the effectiveness of the different types of the fermentation processes in H_2 production from wastes, the type of the waste used is a very important factor. For example, as observed in Fig. 1, the type of the wastes plays a key role to determine the metabolic pathways of the organic matter resulting in variable extent and rates of H_2 production. It has been reported that 2-4 mol H_2/mol hexose can theoretically be produced by dark fermentation. The proportions of the various VFAs produced during dark fermentation, which are affected by diverse factors particularly type of the wastes, are very effective in more exact proportion of 2-4 mol H_2/mol hexose range [39].

In addition, as can be observed in Tables 2 and 3, the biodegradability of the wastes is another key factor affecting this process. In addition, the type of the microbial community, hydraulic retention time (HRT), temperature, organic loading rate (OLR) and pH are some of the other important parameters impacting fermentation process performance [40-42].

As shown in Table 2, limited removal efficiency of chemical oxygen demand (COD) is regarded as the most critical drawback in this process. This parameter can particularly be very challenging in wastewater treatment. Therefore, the integration of the fermentation and other processes, e.g. fermentation and membrane technology, dark and photo fermentation are regarded as the applicable solutions to tackle this challenge. Furthermore, the combination and hybridization of dark fermentation process with other different processes [36], along with the optimization of the operating conditions through different procedures, e.g. the advanced models are regarded as the other future research trends for this process [36, 43-45]

Table 2.
The operating conditions and performances of dark fermentation process.

Process	Bio-waste	Inoculum	Temp. (°C)	pH	HRT	OLR	COD removal efficiency	H_2 production	Reference
Dark fermentation	Manure and food waste	Activated anaerobic sludge	55	6.5	48 h	28.2 g volatile solid (VS)/d	-	16.5 mL H_2/g VS	[40]
Dark fermentation	Food waste (Melon residues)	Activated anaerobic sludge	25	5.6-5.8	20 & 27 h	107.6 g/L	21%	395.5 mL H_2/g VS	[35]
Dark fermentation	Food wastes (mixed fruit wastes)	Activated anaerobic sludge	55	5	5 d	-	-	553 mL H_2/g VS	[41]
Dark fermentation	Food waste	Activated anaerobic sludge	37	6	0.7-1.2 d	150 g COD/L	-	17 mL H_2/g VS	[46]
Dark fermentation	Food waste and white mud from ammonia–soda process	Sewage Sludge	55	5.5	36 h	270.6 g/L.d	-	145.4 mL H_2/g VS	[47]
Dark fermentation	Pig manure	Activated anaerobic sludge	55	5	24 h	48.2 g VS/L.d	-	96.4 mL H_2/g VS	[42]
Dark fermentation	Cow dung	Manure	60	6.6-5.4	8 d	-	-	0.743 mL H_2/ g cow dung	[48]
Dark fermentation	Corn stalk	Cow dung compost	36	7		-	-	144.3 mL H_2/ g corn stalk	[49]
Dark fermentation	Cheese whey and buffalo manure	Anaerobic digested sludge	55	4.8-5	12 d	2.1 g VS/L.d	-	152.2 mL H_2/g VS	[50]
	Pig manure and rice straw	Anaerobic digested sludge	55	5-5.5	4.5 d	-	18%	44.59 mL H_2/g VS	[51]
Dark fermentation	Swine manure	Mixed culture of fermentative bacteria	37	5	16 h	-	-	830 mL H_2/g VS	[52]

Table 3.

The operating conditions and performances of photo and combined dark-photo fermentation processes.

Process	Bio-waste	Inoculum		Temp. (°C)		pH		HRT (h)		Light intensity (Lux)	H_2 production			Reference
		Dark	Photo	dark	photo	dark	photo	dark	photo		Dark fermentation	Photo-fermentation	Total	
Photo-fermentation	Corn Stover	-	Photosynthetic bacteria HAU-M1	-	30	-	6.5	-	120	7000	-	58 mL H_2/g VS	58 mL H_2/g VS	[53]
Dark and photo-fermentation	Cassava	Cattle dung compost	*R. sphaeroides*	37	30	6.8	7	72	268	4000	199 mL H_2/g cassava	611 mL H_2/g cassava	810 mL H_2/g cassava	[39]
Dark and photo-fermentation	Food waste	Cattle dung compost	*R. sphaeroides*	37	30			72	168	4000	220 mL H_2/g food waste	451 mL H_2/g food waste	671 mL H_2/g food waste	[39]
Dark and photo-fermentation	Cassava starch	mixed anaerobic bacteria	Mixed photosynthetic bacteria	31	30	6.3	7	-	-	6000	351 mL H_2/g starch	489 mL H_2/g starch	840 mL H_2/g starch	[54]
Dark and photo-fermentation	*Chlorella sp.* biomass	Anaerobic sludge	PNSB *Rhodobacter sphaeroides* TISTR 1952	35	37	6	7	4.7	0.23	5000	47.2 mL H_2/g VS	125 mL H_2/g VS	172.5 mL H_2/g VS	[55]

2.2. Microbial electrolysis cell

MEC is a process in which electro-genic microorganisms utilize substrate to generate hydrogen. Single and double chamber reactors are two common types of configurations for MEC. Two electrodes as anode and cathode are installed in the related chambers and linked using an external circuit. The substrate present in wastewater is consumed by some electro-genic bacteria producing electrons and transfer to the anode by two general mechanisms, i.e. indirect and direct electron transfer. The first one is carried out by soluble mediators, and the second one is conducted by nanowires and membrane proteins. Coulombic efficiency as well as cathodic hydrogen recovery, which are the ratio of the potential electrons recovered from organic matters to the actual one in anode and the ratio of the potential hydrogen recovered in cathode to the actual one respectively, are two of the vital factors affected by different operating parameters [1]. Mild operation conditions are regarded as one of the important merits of MECs; however, by virtue of some barriers, e.g. thermodynamic and further energy requirement, the MEC cannot automatically run. Therefore, limited power (0.11 V) is required to run the MECs for hydrogen generation from acetate which is 10% lower than the usual required power for water electrolysis (1.23-2 V) [56]. This process is regarded as an emerging and high potential process with some limitations for scaling up like less mass transfer and energy loss [56, 57]. The challenges of this process are classified in five different categories, i.e. anode (methanogenic electron losses, electrode resistance and metabolic diversity), cell design (complex wiring, single vs two chambered, stack configuration and scale-up), power source (using high carbon footprint electrical energy and external energy demand), membrane (long-term stability, bio-fouling, pH imbalance, high cost, substrate and gas crossovers) and cathode (side reaction, long-term stability, electrode resistance and high catalyst cost). Tackling all of these challenges to improve the efficiency of the process is the future research trend of this process. In addition, great capability of this process for coupling with different other processes to produce more and sustainable energy [56, 58] as well as application of new and robust models are recognized as different items for future research trend in this field [1].

As presented in Table 4, high rate of H_2 production and treatment efficiency belong to MEC processes using fermentation liquid as influent. In fact, the best results were obtained using a combined fermentation and MEC process [58]. Therefore, similar to the fermentation process, the hybrid MEC processes showed great performance in both H_2 production and waste treatment efficiency.

Table 4.

The operating conditions and performances of single MEC and hybridized MEC/AD processes.

Process		Bio-waste	Inoculum	Temp. (°C)	pH	Influent COD (mg/L)	COD removal (%)	H_2 production	Reference
Overall process	Sub-process								
AD-MEC		Fermentation liquid of waste activated sludge	Aeration tank effluent	22	7	6458	Up to 60	1200 mL/g COD	[59]
MEC-dark fermentation	Dark fermentation	Corn stalk	Cow dung compost	36	7	20000	-	129.8 mL/g corn stalk	[60]
	MEC	Effluent from dark fermentation	Fermentation bioreactor	36	7	3000-12000	44	257.3 mL/g corn stalk	
AD-MEC	AD	Food waste	Anaerobic granular sludge				26.1	49.4 mL/g VS	[58]
	AD-MEC	Food waste	Anaerobic granular sludge	30	6.5-7.5	2500-3500	34.9	511.0 mL/g VS	

2.3. Pyrolysis

Pyrolysis is a process by which some solid wastes e.g. biomass can be decomposed in the absence of O_2. Generally, gas, liquid and solid products are generated in pyrolysis process; however, the proportions of each phase depend on the operating conditions. Process temperature, residence time and vapor residence time are the key factors that can affect the proportions of the final products in each phase in this process. In general, high temperature along with long residence time are more appropriate for the purpose of gas production, while short residence time of vapor and mild temperature are suitable for producing liquid products. Furthermore, long vapor residence time coupled with low temperature are more appropriate in order to produce charcoals as the end product [61]. There are three subcategories of pyrolysis, i.e. fast, mild and slow pyrolysis [61-63]. Pyrolysis has been used for several centuries for the production of charcoal; however, the fast pyrolysis has attracted more attention in the recent decades because of interesting properties such as running the process at a relatively mild temperature of approximately 500 °C and with a short residence time of less than 2 s [61]. It is noteworthy that the fast pyrolysis is more appropriate for liquid production than the gas and solid phases production. Furthermore, tar and char are unfavorable products in pyrolysis process reacting with gaseous molecules, decreasing gas production and producing undesirable products. Therefore, these are considered as some of the challenges in hydrogen production during pyrolysis process [63]. The effects of some important factors such as moisture, density and composition of the materials pyrolyzed affecting more H_2 production will be discussed below [62].

The composition of the materials used in pyrolysis has demonstrated a considerable influence on H_2 production yield. Biomass, which is considered as one of the most appropriate materials for H_2 production by pyrolysis, is mostly composed of lignin, cellulose and hemicellulose, among which the higher the lignin content, the higher the proportion of H_2

production. Lignin has a high thermal stability in a temperature range from 150 to 900 °C, which can be the reason for high capability of lignin for H_2 production. The density of the waste materials used is another factor affecting the proportion of H_2 generated by pyrolysis. As the materials with a lower density have less falling velocity in a reactor, there is more time to crack the hydrocarbons (HCs) and generate more H_2. Moisture content of the materials pyrolyzed influences the decomposition rate of the materials and the types of final products over pyrolysis process. Generally, the more excessive the moisture content, the higher energy consumption and lower efficiency of the process. Therefore, it has been estimated that a 7% moisture content in pyrolyzed materials is regarded as a suitable proportion for all pyrolysis processes [62]. Furthermore, to enhance the performance of the pyrolysis, this process is more widely studied in hybrid or combined mode. Table 5 presents the overall operating conditions as well as the proportion of H_2 production form wastes. In addition, modeling is another option investigating different aspects of this process to enhance the controllability, product yield and efficiency of this process. However, insufficient validation is known as the main challenge in this regard. Some of the applied models in this process are computational fluid dynamics (CFD), distributed activation energy model (DAEM) and artificial intelligence based models, e.g. artificial neural network (ANN) and adaptive network-based fuzzy inference system (ANFIS) [64]. The application of the new modeling procedures with higher capabilities is gaining attention as a new tool in renewable energy research. Moreover, the determination of the gas products in this process is regarded as another crucial research field by virtue of the harsh environment, in a way that design and application of more advanced sensors to detect the products and process condition over running the process has great importance [64].

2.4. Gasification

Gasification is a thermochemical process by which different types of compounds, e.g. organic wastes can be converted into useful products like H_2 under O_2-deficient condition [63]. There are two common gasification processes for H_2 production from organic substances including steam critical water gasification and steam gasification [63].

The steam critical water gasification usually happens in supercritical state of water (374 °C and 22.1 MPa), in a way that the liquid and gas states of water are miscible under this condition, when supercritical water as an oxidant can react with organic matter (e.g. HCs) molecules and generate CO_2 and H_2. Although this is regarded as an interesting process for potentially high H_2 production from organic matter, the need for higher moisture content of the organic matter along with higher final cost of the produced H_2 than that of direct methane reforming are some limitations of this process [63].

Based on the process temperature conditions, the supercritical water gasification is classified into aqueous phase reforming, near critical catalyzed gasification and supercritical water gasification running at 215-265 °C, 350-400 °C and > 375 °C, respectively. The main products from these three categories are H_2 and CO_2, CH_4, and H_2 and CO_2, consecutively. Overall, this type of gasification process is running at lower temperatures (approximately 600 °C) than the dry gasification at 800-1200 °C. As this type of process takes advantage of water as medium, it is considered as an appropriate process for the application of wet materials in gasification [65].

Regarding the steam gasification, it needs a medium for reactions that may be a mixture of subcritical steam, O_2 and air. The final products are tar, N_2, HCs, CO_2, H_2O, CO and H_2 from air gasification, HC, CO_2, CO and H_2 from O_2 gasification, and tar, light HC, CO_2, CO, CH_4 and H_2 from steam gasification processes, respectively. The average H_2 contents in final products of these processes are 15%, 40% and 40%, and their operating temperatures are in ranges of 900-1100 °C, 1000-1400 °C, and 700-1200 °C, respectively. From the cost point of view, the most expensive one is O_2 gasification followed by the steam and air gasification [63].

Recently, these processes are more often running as a hybrid process with various catalysts. Mass and heat transfer among the particles can be simply carried out in the presence of catalysts, which increase the process performances in H_2 production [63]. Agglomeration and carbon deposition are two of the most important challenges in more efficient applications of the catalysts in this process; therefore, the application of different new and advanced procedures in design and synthesis of the catalysts is one of the hot research topics in this field [66, 67]. Table 5 indicates the different operating conditions of the catalytic gasification processes as well as their H_2 production performances.

2.5. Plasma

Plasma is a collection of ions, free electrons, radicals and neutrals [68, 69]. In 1879, plasma was identified as the fourth state of matter by William Crookes, and systematically studied by Langmuir in 1929 [70, 71]. Adequate and continuous energy is needed to generate and sustain the plasma, as otherwise the plasma components will be converted into neutral components. From the aspect of temperature, plasma can be categorized into two classifications, i.e. non-thermal and hot plasma. In non-thermal plasma, there is a considerable difference between the temperatures of electrons, ions and neutral gas [70]. In a way that depending on the applied procedure for plasma formation and the background gas used, the temperature of the electrons in non-thermal plasma can be varied from 10,000 to 100,000 ℃. Whilst the other components of the plasma will be at room temperature [72]. However in hot plasma (3727-19727 ℃), the temperature of electrons is the same as other species of the plasma [70]. In addition, there are other classifications for plasma conducted by the plasma discharge procedures including microwave, radio frequency and direct current, and reactor configurations, i.e. plasma spout bed reactor, plasma entrained bed reactor, plasma moving bed reactor and plasma fixed bed reactor [70]. There are many applications for plasma, such as environmental remediation [69], coating [73, 74], membrane synthesis industry [71, 75], sterilization and gasification [70]. Plasma gasification uses external power to increase and retain the temperature of the background gas and plasma components. During this process, the organic substances are broken down into their components via the active species, and the final materials produced are ash, slug and syngas [76]. In this process, the mass and quality of the produced gas are affected by some operating parameters like steam stream plus reaction temperature, oxidant, plasma gas flow rate and residence time. Regarding the mentioned nature for this process, plasma gasification has a considerable flexibility in receiving a wide spectrum of wastes and release very small volume of pollutants, e.g. metals (mercury) and PM needing further treatment [77]. In addition, great controllability as well as high reactive activity and high enthalpy value are other known merits of this process [78]. In order to enhance the performance of this process in different applications for H_2 production, the hybrid form of this process such as catalytic plasma and thermal plasma pyrolysis has been considered [76].

Table 5.

The operating conditions and performances of pyrolysis, gasification and plasma processes.

Process	Bio-waste	Catalyst	Temp. (ºC)	H_2 production/biomass	Reference
Catalytic-pyrolysis	Municipal sludge	Dental waste-derived sodium zirconate	900	142 mL/g	[79]
Catalytic-pyrolysis	Algae (Spirulina)	Dental waste-derived sodium zirconate	900	205 mL/g	[79]
Catalytic-pyrolysis	Methylcellulose	Dental waste-derived sodium zirconate	900	197 mL/g	[79]
Catalytic pyrolysis	Olive pomace	Ni-OPC	700	320 mL/g	[80]
Catalytic pyrolysis	Biomass of water hyacinth	$FeCl_3$	540	117 mL/g	[81]
Catalytic steam gasification	Palm oil wastes	Tri-metallic (nano-NiLaFe/γ-Al_2O_3)	800	441 mL/g	[82]
Catalytic gasification	MSW	CaO	750	278 mL/g	[83]
Catalytic gasification	Corn stalk	CaO	650	574 mL/g	[84]
Catalytic gasification	Rice straw	CaO	650	567 mL/g	[84]
Catalytic gasification	Wheat straw	CaO	650	581 mL/g	[84]
Catalytic gasification	Peanut shell	CaO	650	586 mL/g	[84]
Thermal plasma gasification	Paper mill waste (PMW)	Combined water gas shift and pressure swing adsorption	1400-1450	400 NmL/g	[26]

The hazardous, toxic and resistant wastes cannot be easily decomposed and converted into H_2 by biological processes; therefore, pyrolysis, gasification and plasma processes are more suitable for the treatment of such wastes and generate H_2 simultaneously. As observed in Table5, the gasification-based processes have shown better potential to produce more hydrogen followed by plasma and pyrolysis-based processes regardless of the operating conditions and type of the wastes used. As indicated in Table 5, the highest H_2 produced belongs to catalytic gasification of peanut shell with 586 mL H_2/g biomass. However, one of the most important drawbacks is that during these processes, both valuable gas (i.e. H_2) and harmful gases (e.g. CO_2, CO) are produced. Therefore, additional separation or treatment procedures are required to recover H_2 while removing or detoxifying hazardous gases, which will inevitably involve additional energy and cost.

3. Techno-economic analysis

Currently, approximately 98% of the hydrogen gas is produced by the consumption of fossil fuels using methane gas reforming or coal gasification methods, with which the main challenges remain the same as fossil fuels such as unsustainability, GHG emissions and global warming. Therefore, there has been a major shift towards the production of biogases from renewable biomass sources [85], based on the principles and importance of life cycle analysis (LCA).

TEA is a methodology framework to analyze the technical and economic performance of a process, product or service. TEA is a study performed on any industrial process to assess its profitability [86]. This type of study is usually performed on new technologies that show great lab-scale performance and have potential for commercialization. TEA describes both the economic performance and environmental impacts of the process, in both short-term and long-term [87]. TEA is also used to analyze the profitability and GHG emissions of new methods for the treatment of waste and wastewater that are biomass-based [88, 89]. In this way, bio-waste and relevant wastewater containing biomass materials have a great potential to produce hydrogen gas as a clean source of energy to both decrease the GHG emission and by-product wastes and enhance the economy of the relevant industry [86, 90, 91]. For this purpose, general economic and technical conditions of the hydrogen production from biomass sources were studied using both lab-scale data and simulation software. The obtained results about various hydrogen production processes form biomass-based sources revealed that the economic part of the TEA directly depended on the maturity of the technology, availability and cost of bio-waste or wastewater, the market demand for hydrogen, and the capital and operational costs of the process [92-94].

From techno-economic point of view, the optimum scenario is to increase the hydrogen gas productivity and to decrease both the capital and operational costs, which will increase the feasibility of commercial-scale hydrogen production from biomass waste and wastewater. The capital cost relates to the land requirement and facilities, and operational cost relates to the supplementation and transportation of the feedstock and other required materials [63, 95, 96]. However, the development of the technology and the local condition play an important role in the determination of the both capital and operational costs. Therefore, it is not possible to make a general rule for all cases [86]. In this way, an optimum value is obtained using simulation software like ASPEN or Hysys, concerning the optimum size of the plant and annual return rate of the costs according to the local price of hydrogen, feedstock, transportation, and materials [86, 87].

The maturity of a technology and its development is one of the most important obstacles in the way of commercialization of biomass-based hydrogen production technology. While the Technology Readiness Level (TRL) for traditional methods is adequately high (TRL 8) to reduce the production cost, the biological or electrochemical process for biomass conversion have TRL less than 5 that dramatically increases the production cost [95, 97-99]. Furthermore, high price of the biomass-based feedstock and relevant operating costs (e.g. transportation) increase the biogas production cost for these types of processes. These expenditures therefore cause the production cost of hydrogen using biomass materials to be in the range of 1.2-2.4 US$/kg, while natural gas reforming can produce hydrogen with cost of less than 0.8 US$/kg [88, 100]. To move forward, different hydrogen production methods using waste as feedstock will need to conduct their individual economic analysis and LCA. In general, the production cost of hydrogen gas should be close to 0.3 US$/kg H_2 which is equivalent to the price of gasoline (2.5 US$/GJ), in order to increase the commercial favorability of a production process [101].

3.1. Process economics

The potential capacity of Turkey as a sample country for the production of biogas and hydrogen from wastewater of the milk-processing factory was investigated [72]. The results revealed that annually more than 50 million m^3 of biogas and about 13000 ton of hydrogen gas can be produced by the treatment of wastewater from milk-processing plants. In addition, the energy efficiency of the simulated plants can reach 70% and 48%, respectively and the energy saving of the processes can reach the value of 15 million US$/yr [96].

The effective treatment of bio-waste such as agricultural waste, MSW and wastewater as well as the production of biogas are the first step of commercialization, and most efforts are performed in lab-scale to evaluate the efficiency of different methods. On the other hand, the process economy plays the dominating role in large-scale production; therefore, the lab scale results are coupled with simulation modelling to estimate both the production and economic efficiency of large-scale systems. In practice, the lab-scale results are used for the prediction of large scale systems using a simulation software e.g. ASPEN Plus [92].

The maturity of a technology and its development is one of the most important obstacles in the way of commercialization of biomass-based hydrogen production. TRL has been introduced to grade the maturity of technology for its readiness to commercialization. TRL is a number from 1-9, with higher TRL values demonstrating more well-developed technology which is closer to economic and cost-effective commercialization. The TRL commences with a value of 1 that shows the process is at basic technology research stage, then increases to higher values revealing research for evaluation of feasibility, development of technology, development of the system, and finally the operation test of the system, which is equal to TRL 9 [4]. Although the simulated results provide a detailed view about the economic feasibility of the process, they cannot be used without constraints. In other words, the derived results are obtained according to the initial local economic and environmental conditions, which will vary between countries or even between different regions of the same country.

For example, Li et al. [102] have used dark fermentation process for the production of hydrogen from biomass. In their study, the hydrogen was produced from both wastewater and agricultural waste in lab scale and ASPEN Plus was used for estimation of large-scale production. Their results demonstrated that the maximum annual profit would be obtained by a working volume of 100 m^3 of wastewater and 400 m^3 of agricultural waste that respectively obtained annual return of 81% and 30%. It was estimated that on local price evaluation, the revenue of biogas production is approximately 2.7 million US$/yr from the wastewater treatment and 2 million US$/yr from the treatment of agricultural waste. Such economic analysis shows a high feasibility of commercialization for hydrogen production from agricultural wastes and wastewater.

In other studies, the economic efficiency of various biomass-based plants for the production of hydrogen gas was estimated. The production cost of H_2 biogas in different processes is directly dependent on the facilities used for treatment process as well as the efficiency of the process. Therefore, from a commercial point of view, both the production efficiency and instalment and operational cost should be fully considered. For example, the electrolysis system can be used for hydrogen production with a conversion efficiency of about 50%, as a result, the hydrogen production cost is 10 US$/kg, which is much higher than gasification process [103]. The economic evaluation performed on different gasification process showed that the average hydrogen production cost is about 1.7-2.2 US$/kg [93, 104]. However, the efficiency of the gasification process depends on the method used. This process can produce up to 190 g H_2/kg of agricultural waste [94, 105]. In a study, the fluidized bed (FB) gasification process could produce cheaper hydrogen gas compared to entrained flow (EF) gasification, but the thermal efficiency of the EF is much higher than FB [89].

Beside the favorable results of both FB and EF gasification processes, the high price of biomass is the main obstacle for commercialization. The financial analysis shows that the biomass price should be less than 60 US$/ton in order to produce hydrogen at a price which can cover the cost of the process. However, gasification process with carbon capture can be followed to simultaneously produce and sell CO_2 that can compensate for the higher price of the biomass feedstock [89] .

In general, the gasification process is the most commercialized method for hydrogen production. In this method, the average thermal efficiency of the hydrogen is about 50%, which is in the moderate range. Furthermore, the levelized cost of hydrogen (LCOH) production from biomass sources is in a wide range of 1.4-5.2 US$/kg, which highly depends on the scale of the system and the biomass waste cost. Salkuyeh et al. [80] investigated the effect of cost of biomass on the final cost of hydrogen, and identified the high dependency of the economy of the gasification process on the biomass waste cost, in which the hydrogen gas cost can be as low as 0.5 US$/kg when using zero-cost feedstock to about 4.5 US$/kg [89]. Therefore, the installation of hydrogen production plant in the vicinity of agricultural processing plants that produce large quantities of biomass waste can bring major values to the processing plant. Furthermore, the calorific values of the wastes are different which have a major impact on the plant production efficiency and on the economy and environmental behavior of the process. The pre-treatment process like separation of hazardous materials from feedstock is also an important step of gasification that comprise a potential significant part of the operational cost of project. In addition, securing long-term local supply for feedstock wastes and customers for produced biogases is another important challenge in the overall appraisal of biogas production process [33, 106].

Additionally, different studies showed that the capital cost of the gasification process is in the range of 10-20% of total cost [33]. Although the TRL for gasification process is among the highest and showed adequate maturity in technology development of the process, it still suffers from immaturity of technology for waste pre-treatment. Additionally, the market demand for produced hydrogen is still developing, which may hinder the commercialization of hydrogen production technologies.

In most cases, a single method cannot provide sufficient gas production efficiency to compensate for its cost and therefore combined methods are used to take advantage of more than one method and decrease the hydrogen gas production. Although fermentation process showed suitable capability for agriculture waste and wastewater treatment, different treatment methods follow separate process and generate different process efficiency. In this way, some techno-economic studies were performed to investigate the H_2 production efficiency. Furthermore, it is possible to combine fermentation methods in a single process to increase the production efficiency. Han et al. [83] studied the efficiency of a combined system of both SSF and dark fermentation for the production of hydrogen gas from a plant having the treatment capacity of 10 ton/d of food waste. The results show that the annual return rate of plant is more than 20% and the hydrogen production cost is 2.3 US$/m^3, which is 0.4 US$/m^3 cheaper than market price of H_2 [107]. The study has proven the feasibility of the fermentation process for biogas production.

In another study, a combination of dark fermentation and photo fermentation was used to produce hydrogen gas from sugar factory waste and to evaluate the effectiveness of the combined system. The wide availability of sucrose-based waste (e.g. molasses) which decreases the cost of feedstock, and high content of amino acids and other organic materials that prepare grounds for rapid growth of microorganisms increase the favorability of this type of biomass wastes for hydrogen generation. However, a computer-based analysis of this combination of processes showed it to be unfavorable from economic point of view due to the high cost of photo fermentation stage [108]. Additionally, some other studies revealed that the H_2 production cost in fermentation processes highly depends on the photo fermentation, due to low productivity of this step that increases the needs of high volume of fermentor and large space requirements. In addition, the conversion efficiency of the photo fermentation process is less than 5%. The most significant part of this cost is due to the cost of plastic tubing for the photo fermenters that contribute more than one third of hydrogen production cost [109]. Additionally, as acids are produced during the fermentation process, and the hydrogen productivity of the process is dependent on the pH that needs accurate adjusting and control, thereby increasing the overall cost of the process.

MEC is an exciting hydrogen production process due to dramatic decrease in its electrical consumption, and no need for pre-treatment or purification, therefore increasing its economic competitiveness. On the other hand, the high cost of catalyst, high susceptibility to CO poisoning, and low hydrogen production (~70 g/kg of feedstock) were its disadvantages [110]. The anode and collector materials comprise 94% of the total material costs of MEC, which accounts for significant part of the process [111]. A lab-scale MEC was used for the production of hydrogen form renewable sources, and hydrogen production rate of 120 mL/L.d was achieved, although its economy is not so optimistic [112]. The lab-scale results suggested that by the development of technology towards higher TRL, the MEC process could generate better large-scale performance.

Pyrolysis is another straightforward method for the treatment of agricultural waste and production of hydrogen. The pyrolysis process is relatively simple, can be performed in large-scale, and possess a high TRL 7, which will decrease its capital costs. However, the high emissions of GHG like CO_2 caused LCA challenges for this method. In the lab-scale system, the hydrogen production rate of the process was 65 g per kg of rice husk biomass and purity of 60% was achieved that shows moderate-to-high quality of this process for commercialization. In the pyrolysis process, the hydrogen yield and tar residue consumption were increased by increasing the temperature that increase the operational cost of the process as well [63]. In another study, the fast pyrolysis method was used to model the process of hydrogen production from corn waste and results demonstrated that the production cost of hydrogen was 2.1-3.1 US$ per kg of hydrogen. The simulation results also revealed the high dependency of the process cost on the price of biomass feedstock [90, 91].

Plasma gasification is a new generation of methods for the production of hydrogen gas. The most economical advantage of the plasma gasification is its complete conversion of carbon materials with no organic waste residues. The application of plasma is more dominant in a catalytic reaction process, because plasma can convert all materials that may have poisonous effect on the catalyst and bypass the pre-treatment step. This process can be cost effective for the production of biogas. However, due to the high operation cost from its high electrical power consumption, this method is very expensive for the treatment of high volume of agricultural waste and is mainly used for the gasification of special types of wastes like printed circuit boards, medical wastes, or metallurgical wastes. The power consumption of this method may reach more than 20% of the costs of the plant [33]. In a study, plasma was used in gasification process in small-scale system and the hydrogen cost was 2.4 US$/kg, which is comparable with commercial gasoline. The results show high potential of plasma for special waste treatment application to produce hydrogen gas [113]. Table 6 summarizes the produced H_2 cost, and TRLs of the reviewed processes for commercial situation of all these processes.

As observed in Table 6, the gasification process has been commercialized and the cost of produced H_2 by this process is lower than the others. From the aspect of less H_2 price, there is almost same condition for dark, solid state and with roughly 2.3 US$/kg followed by plasma with 2.4 US$/kg, pyrolysis with approximately 2.6 US$/kg, MEC and photo-fermentation with around 2.8 and 3.5 US$/kg consecutively. From the TRL point of view, gasification process with TRL 9 has ranked the first followed by pyrolysis, dark fermentation, SSF, photo-fermentation, plasma and MEC in decreasing order.

4. Life cycle analysis

LCA is considered as a beneficial procedure to detect the environmental hotspots and demonstrate the possible emissions during a process, therefore appropriate solutions can be brought up to minimize the undesirable environmental effects [114]. A standard LCA procedure is conducted based on the ISO 14040 and ISO 14044, according which there are four stages, i.e. goal and scope definition, life cycle inventory, LCA and interpretation [115].

Table 6. The economic, commercialization, and technology readiness level of H_2 production processes from biomass

Process	H_2 production cost (US$/kg)	Commercial scale	Hydrogen production (g H_2/kg biomass)	TRL	Reference
Fluidized bed gasification	2.1	Small scale	-	9	[88, 100]
Plasma	2.4	Lab-scale	-	4	[33, 113]
Gasification	1.7–2.2	Large scale	50-180	9	[63, 89, 107]
Natural gas reforming	0.8	Large scale	35-110	9	[100]
Gasoline price	0.3	Large scale	-	9	[101]
Electrolysis	3.5- 10	Lab scale	20-85	4	[103]
Dark fermentation	2.3	Pilot scale	8-45	5	[102, 107, 116]
Photo fermentation	3.5	Lab-scale	9-45	4	[117, 118]
SSF	2.29	Lab-scale	15-32	5	[119, 120]
Pyrolysis	2.1-3.1	Medium scale	25-55	7	[90, 91]
MEC	1.1-4.5	Lab scale	70	2-4	[121, 122]

In the first stage, the purpose of the LCA in H_2 production systems is the quantification and detection of the emissions to the abiotic and biotic environments during all steps of the process. In addition, the assessment of the environmental impacts of the required energy and materials during H_2 production and utilization processes along with giving appropriate solutions to decrease these detrimental effects are taken into account as another general purpose of this stage. In second stage, all inputs and outputs of the defined boundaries are quantified and compilated [115]. In third stage, the outcomes of the second stage are classified into different impact classifications, e.g. human toxicity through soil, through water and through air along with some indexes like global warming potential, ozone depletion, water consumption and resource consumption. Then, indicators which have been defined in scientific documents are used to estimate the potential impact of each item such as different resource usages and each emission. In fourth stage, the outcomes of the first three stages are reviewed, argued and interpreted. During this stage, the appropriate solutions to decrease the detrimental effects are recommended [115]. LCA of different biogas production systems have been analyzed to address their environmental characteristics. However, since there are some limited and sporadic studies for LCA assessment of hydrogen production processes from organic waste, the related and comparable studies were listed in Table 7 and discussed below.

The comparison of different studies revealed that production of hydrogen gas from biomass sources could decrease the GHG emission. The biomass-based plant can produce up to 75% lower GHG compare to natural gas reforming process. In this way, gasification process showed dramatically lower CO_2 emission and fossil fuel demand compare to reforming processes [20].

For study of the cradle-to-grave LCA, it is mandatory to cover the impact of different parameters include raw material production, pre-treatment, collection, transportation, biogas production process, and hydrogen purification, transportation and application [123]. The comparison of different studies showed better LCA of biomass to hydrogen processes, compare to production of hydrogen form coal. The results showed that in process of production of hydrogen, life cycle energy consumption of biomass-based process is about one-fourth of coal-based process. Furthermore, about 90% less GHG were emitted by using biomass materials. In addition, pipeline is most environmentally friendly method for the transportation of produced hydrogen and has less GHG emission [124].

Although the economic competitiveness of hydrogen production form biomass material is still to be improved, its environmental friendliness and low GHG emission increase the motivation to increase the maturity of such technology towards commercialization. More than 98% reduction of GHG emission by using biomass material has shown great long-term positive impact on mitigating global warming [125]. However, the source of biomass makes a big impact on LCA of the process. Using biomass resources that produce a high yield of H_2 gas, such as eucalyptus, will improve the economics and LCA result [126].

From environmental point of view, LCA of plasma gasification was performed in some studies and results showed that plasma gasification has better saving in the energy and material resources. Furthermore, the amount of GHG emission, freshwater and air pollution was lower compare to incineration, and higher amount of energy was produced. Overall, plasma gasification showed negative values for all investigated environmental categories, which reveal higher environmental advantageous [127].

On the other hand, LCA was performed to compare two gasification processes, i.e. fluidized bed (FB) gasification and entrained flow (EF) gasification. The results showed that the life cycle energy of the EF system is 20% less than the FB system, which demonstrates a better environmental performance of EF system [89].

Table 7.

The life cycle assessment of the H_2 production processes from biomass.

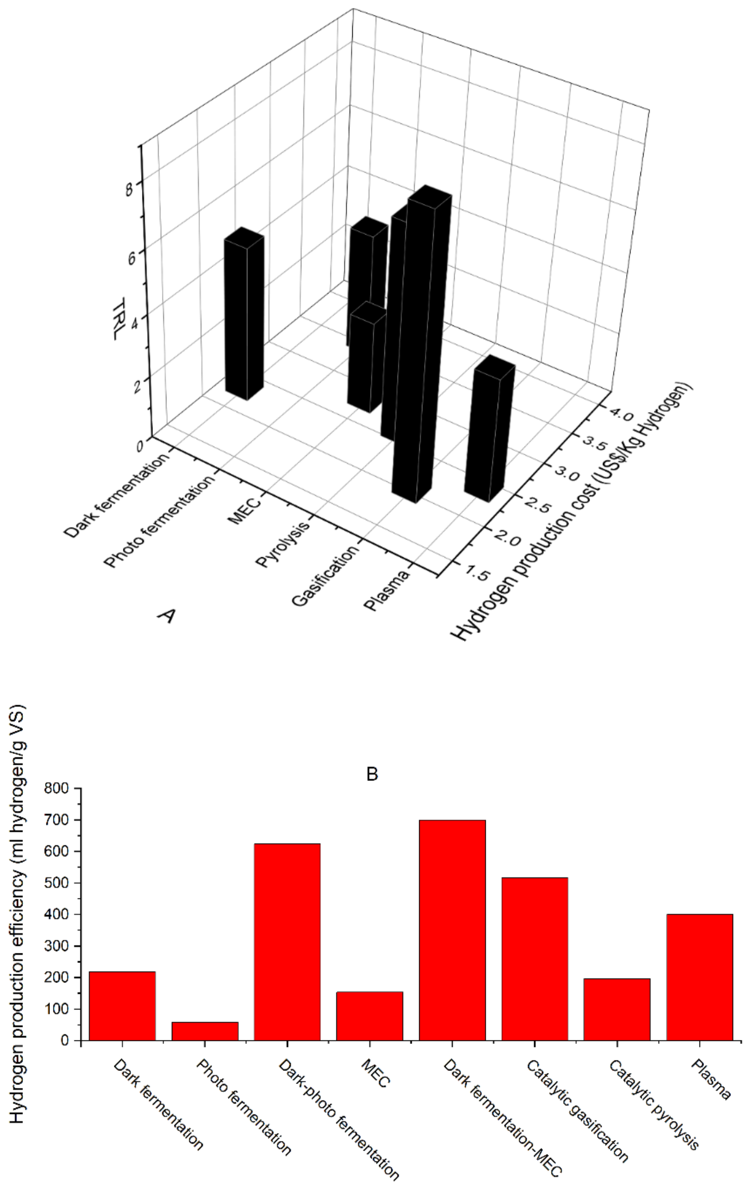
Process	Bio-waste	Final fuel products	Net GHG emissions	Reference
Fermentation	Food waste; microalgae	CH_4, H_2	15.1 kg CO_2-eq/kg H_2	[128]
MEC	Urban wastewater	H_2	18.8 kg CO_2-eq/kg H_2	[114]
Gasification	Coal	H_2	18.0 kg CO_2-eq/kg H_2	[114]
Plasma Gasification	MSW		31 kg CO_2-eq/kg MSW	[127]

According to the results reported in Table 7, the dark fermentation process generates the lowest production of 15.12 kg CO_2-eq/kg hydrogen, and is therefore the best process among the gasification, plasma and MEC, on the basis of GHG emissions. It is worth highlighting that Rosen [129] has highlighted the importance of the advanced sustainability assessment tools such as exergy and its combinations with LCA and economic analysis, i.e., exergoenvironmental and exergoeconomic analyses in biofuel industries which can be applied for investigation the sustainability features of various H_2 production platforms as well; however, there is a big knowledge gap in this regard which can be taken into more consideration in this field. In addition, Soltanian *et al.* [130] critically reviewed the exergetic aspects of lignocellulosic biofuels suggested the exergoenvironmental and exergoeconomic procedures as two more comprehensive and advanced tools to analyze such systems and make a right decision.

5. Process comparison for efficiency, economics and environmental impacts

In order to prioritize different processes to apply for H_2 production from organic wastes, there is a strong need to compare the capabilities of the processes from aspects of efficiency, economics and environmental footprint. Therefore, regarding the presented information in Tables 2-5, the average values of H_2 production by different single and combined processes were calculated and presented in Fig. 2. For economic comparison, the average cost of the H_2

produced is shown in Table 6 and the TRL of the processes are demonstrated in Fig. 2. Although there is lack of environmental assessment information for all the processes studied, using the information listed in Table 7, the GHG emission potential from different processes is shown in Fig. 2 for comparison.



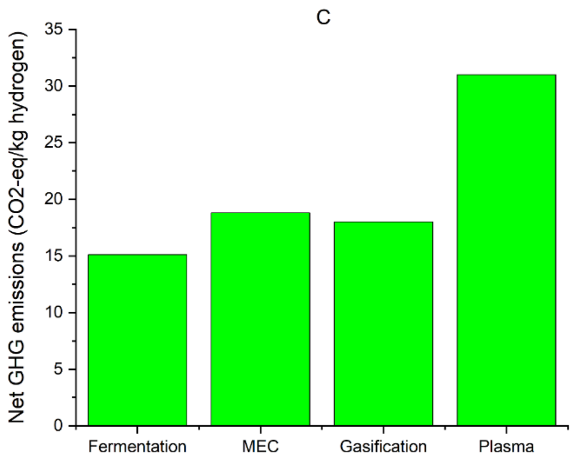


Fig. 2. Comparison of different H_2 producing processes from bio-waste for (A) cost and TRL, (B) efficiency, and (C) net GHG emission.

As observed in Fig. 2B, regarding the H_2 production efficiency, the combined dark fermentation-MEC process was the best process, followed by the combined dark-photo fermentation, catalytic gasification, plasma, dark fermentation, catalytic pyrolysis, MEC and photo fermentation respectively. From the aspect of the TRL, the gasification process ranked first followed by pyrolysis, dark fermentation, photo-fermentation, plasma and MEC respectively. Regarding the cost of H_2 produced, the cheapest process is gasification followed by dark fermentation, plasma, pyrolysis, MEC, and photo fermentation correspondingly. From the GHG emission assessment, the fermentation process was the best, followed by gasification process, MEC process, with plasma process being the worst.

6. Practical implications

The results of the present work underline the capabilities and limitations of the potential H_2 production processes from bio-wastes/wastewaters. In addition, the research trends of these processes are suggested. The selection of an appropriate process for H_2 production from bio-wastes is the first step in the decision making, this study will help the engineers and researchers to compare and choose the best one based on the capabilities and limitations of each process. Based on the initial appraisal, further research may be needed for verification before full commercial operations. Moreover, the findings from this study should support the engineers and researchers to focus on the bottlenecks of the selected processes for further research and problem solving.

7. Conclusions and future research perspectives

To address the increasing global energy demand and environmental challenges, hydrogen production from bio-wastes has gained significant attention. There are several processes for H_2 production from bio-waste such as dark, photo and solid-state fermentation, MEC, pyrolysis, gasification and plasma. This work critically reviewed the capability, limitation and commercial potential of these different processes based on techno-economic and environmental impact analysis. Based on capabilities of the processes for H_2 production, the dark fermentation process showed higher performance than others. Most of the hybrid or combined processes demonstrated great performance in H_2 production from bio-waste, including dark fermentation-MEC, dark-photo fermentation, catalytic pyrolysis, and catalytic gasification. Regarding the production cost, the cheapest H_2 production belonged to gasification at 2 US$/kg and dark-fermentation at 2.3 US$/kg, followed by plasma, pyrolysis, MEC and photo-fermentation. Based on LCA, fermentation produced the lowest GHG emissions followed by gasification, MEC and plasma processes. However, there are still many deficiencies regarding the technological, economic and environmental performances of these processes. Future research should focus on improving the hydrogen production efficiency of the hybrid and combined processes so as to increase their TRL value and reduce the overall cost. Furthermore, the techno-economic and environmental impact assessments are needed especially for emerging hybrid technologies with low TRL, in order to support their transition and adoption in the energy industry. In addition, investigating the sustainability features of the various H_2 production systems through exergoenvironmental and exergoeconomic procedures as two advanced sustainability assessment tools is expected to become future research priority.

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