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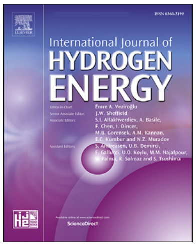

Review Article

A review of hydrogen production via biomass gasification and its prospect in Bangladesh

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ABSTRACT

Hydrogen has been using as one of the green fuel along with conventional fossil fuels which has enormous prospect. A new dimension of hydrogen energy technology can reduce the dependency on non-renewable energy sources due to the rapid depletion of fossil fuels. Hydrogen production via Biomass (Municipal solid waste, Agricultural waste and forest residue) gasification is one of the promising and economic technologies. The study highlights the hydrogen production potential from biomass through gasification technology and review the parameters effect of hydrogen production such as temperature, pressure, biomass and agent ratio, equivalence ratios, bed material, gasifying agents and catalysts effect. The study also covers the all associated steps of hydrogen separation and purification, WGS reaction, cleaning and drying, membrane separation and pressure swing adsorption (PSA). To meet the huge and rising energy demand, many countries made a multidimensional power development plan by adding different renewable, nuclear and fossil fuel sources. A large amount of biomass (total biomass production in Bangladesh is 47.71 million ton coal equivalent where 37.16, 3.49 and 7.04 MTCE are agricultural, MSW and forest residue based biomass respectively by 2016) is produced from daily uses by a big number of populations in a country. It also includes total feature of biomass gasification plant in Bangladesh.

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Introduction

Hydrogen is one of the energy carriers that ensure sustainable energy future [1]. Considering the long term impact of hydrogen for energy and transportation, it would be a primary source that leads the global energy system of the future [2]. Many reviews depict the current and future technologies for hydrogen production, climate policy goal to limit global temperature increment [3], feedstock to produce hydrogen [4], technological feasibility [5], regional support, production cost of different pathways [6]. A remarkable progress of hydrogen production technologies has been made in recent years that open new era and support to design future energy infrastructure [7]. Though, the technology requires a good support to materialize as a whole. A collective global efforts of hydrogen economy should find an inexpensive and green technology, though there are few difficulties in terms of wider commercial use all over the world as a source of energy or fuel. Hydrogen and fuel cell are considered two pillars of the sustainable energy infrastructure [8]. Few key initiatives made strength to upwards the hydrogen economy. Manufacturing, hydrogen storage and transportation, fuel cell, stationary applications, mobility application, infrastructure/fuelling station, code of standards, energy source and fuel, technology acceptance and synergy are ten initiatives that coordinate the total chain of hydrogen economy and have an individual measures [9,10]. Hydrogen is the green energy carrier and very promising source to provide energy for different energy conversion devices such as fuel cells, generator etc. A feature defines the importance of components such as; 1 ton/h or 24 ton/day of mixed waste can produce over 2000 kg/day of hydrogen. The amount is enough for 400 vehicles [11].

Currently, major portion of hydrogen is produced from fossil fuels (natural gas, coal etc.) via thermo chemical processes. Moreover, water photolysis [12] and electrolysis [13,14] also used to produce hydrogen. It would be a most sustainable hydrogen production technology, if the energy source is abandon and sustainable like biomass which is fourth largest source of energy in the universe. It contributes 90% of total energy supply in the developing countries [15] and still considering main source of primary energy feedstock [16]. Pyrolysis, gasification and combustion are commonly used technology to produce hydrogen along with hydrolysis and fermentation [16].

Fossil fuels are main source of energy in the universe. The global demand is estimated to be an approximately 6 billion gallons of oil per day by the year 2050. The universe is approaching to take the unforeseen challenges for environmental deterioration and for sustainable fuels. It would be an uncertain future if all energy demands depend on the source of fossil fuels [17]. The total primary energy consumption in 2016 all over the world was 13,276.3 million tons oil equivalent (mtoe) with an increasing rate of 1.0% over the previous year as shown in Fig. 1 accordingly, the primary energy consumption growth rate around the world remained low in 2016 and the fuel mix shifted away from coal towards lower carbon fuels, whereas renewable power consumption grew by 14.1% in 2016 [18].

Fig. 2 presents the growth of global renewable energy (excluding nuclear and hydro) consumption from 2006 to 2016. This indicates that the world is relying more and more on renewable sources, making biomass an attractive energy source. It is assumed that in next century biomass sources meet up the 50% of the world's energy demand and to reduce GHG emissions that is a sustainable and cost-effective option [19]. Power generation from biomass energy has increased significantly in recent years. More than 800 biomass power plants having a capacity of over 8700 MW have started operation in past few years and the number of active biomass power plant is over one thousand in Europe [20].

Bangladesh is one of the South Asian small countries with 56,977 sq. miles and densely populated with the population of 16.29 crores [21]. Bangladesh produces a vast amount of biomass due to its enormous agricultural activities and high population density. Moreover, the rain-fed ecosystem of the country produces a tremendous amount of biomass. Biomass inherits both the properties of gasoline and characteristics of renewable energy source. In Bangladesh, especially in rural areas, energy demand for cooking and heating is mainly met by biomass. However, biomass has some other uses also. But, all the biomass produced are not utilizing properly that can

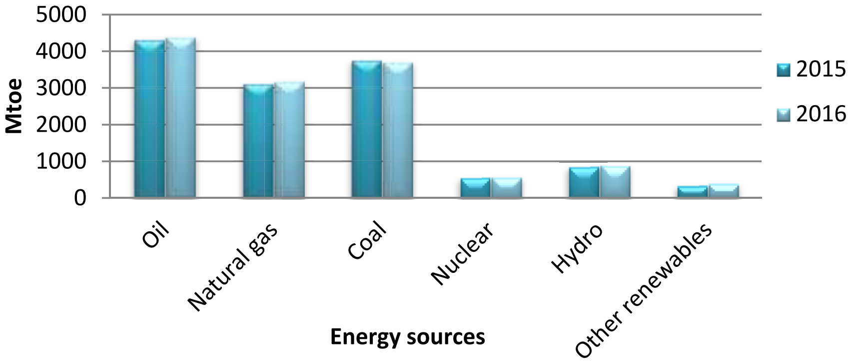

Fig. 1 – World's primary energy consumption pattern in 2015 and 2016 [18].

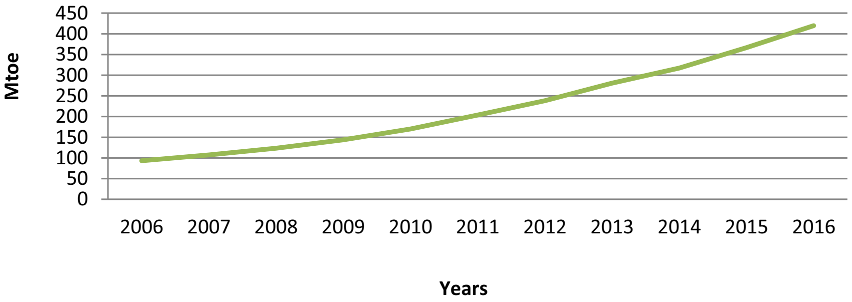

Fig. 2 – Global consumption pattern of renewable energy (excluding nuclear and hydro) [18].

solve our energy and fuel crisis via modern technologies. Thermochemical conversion or gasification is the most commonly used technology for the production of product gas. Many reviews of the last couple of years outlined the conventional gasification along with extended or new techniques to enhance the production rate and purification of hydrogen. The technology is not standardized yet and growing the production plants all over the world to materialize the hydrogen economy according to the hydrogen economy roadmap. Many countries are rich in biomass whereas biomass-derived hydrogen production and purification technologies are still under development stage to use hydrogen as fuel and energy source. Most of the hydrogen production plant is in investigation phases of operation and standardizing parameters that influence the production rate. A critical review of the technologies are very important to get the necessary information and for further establishment to progress. This review aims to merge the common review gap of current research and development on biomass-derived gasification technology to produce hydrogen. It includes the most updated thermal gasification techniques, pros, and cons of different gasification technologies and system parameters to boost up the hydrogen production, purification steps of producer gas. Moreover, includes a brief review of thermal gasification potential of biomass in Bangladesh.

Biomass

Any organic matter which is available on a renewable basis and can be used as an energy source including wastes and residues from various agricultural activities, animal wastes and livestock operation residues, forest remnant, various types of wood and wood wastes, oceanic plants and organic wastes from municipalities can be defined as biomass. It is considered as a very promising source of energy that is renewable all around the globe. It is a sustainable and available source of energy. In contrast with carbon dioxide, biomass consumes a similar amount of CO_2 while growing that it frees during burning as fuel [22]. Moreover, less amount of sulfur in biomass fuel reduces the acid rain [23]. As a result, use of biomass fuel instead of fossil fuel will cause an overall decrease in GHG (greenhouse gas) emissions [24,25].

Sources of biomass

The considerable sources of biomass could be classified as agricultural wastes and residues, MSW (municipal solid wastes)

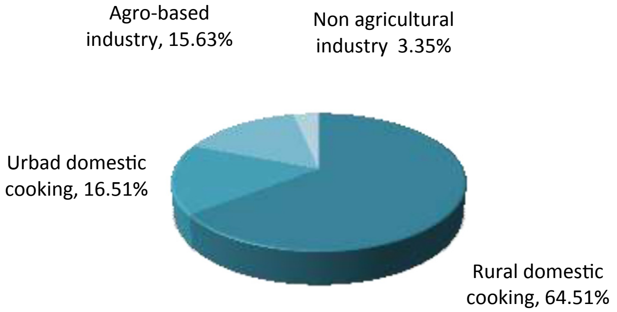

Fig. 3 – Sector wise biomass consumption in Bangladesh.

Table 1 – Source and uses of biomass in Bangladesh.

Biomass type	Biomass source	Residue/Waste	Uses
Agricultural residue and waste	Rice	Husk	Cattle feed, poultry bedding, and Fuel
		Straw	Animal foodstuff, fuel, animal bedding and house building materials
	Jute	Stalk	House building materials and fuel
	Wheat	Straw	House building materials and fuel
	Coconut	Leaf	House building materials and fuel
		Husk and shell	Fuel
	Groundnut	Straw	Animal foodstuff and fuel
	Vegetable	Plants and peel	Animal foodstuff, fertilizer, and fuel
	Potato	Plants	Fertilizer
	Pulse	Straw	Animal foodstuff and fuel
	Cotton	Stalks	Fuel
	Sugarcane	Leaf and tops	Animal foodstuff and fuel
		Bagasse	Fuel
	Maize	Straw and leafs	Animal foodstuff and fuel
		Husk	Fuel
	Animal and poultry	Cow and buffalo dung	Manure and fuel
		Poultry dropping	Manure
		Goat and sheep feces	Manure
		Cattle bedding material	Compost and fuel
Municipal solid waste	Various human activities	MSW	Recycling, fuel, and manure
		Industrial waste	Recycling and fuel
		Kitchen waste	Manure and animal feed
Forest residue	Forrest land	Branches, twigs, and leaves	Fencing and fuel
		Wood	fuel and furniture
		Wood residue	Fuel

and forest residues [26]. Most commonly used biomass for biodiesel generation is rapeseed, while corn and sugar cane are used to generate bio-ethanol. Other resources that generally used are sugar beet, cassava, sweet sorghum and wheat for bioethanol and jatropha, palm oil, soyabean, canola, coconut, peanuts and sunflower seeds for biodiesel [25]. Various cellulosic materials such as woody plants, grassy crops, agricultural by-products, by-products from the forestry (including wood residues, stems, and stalks) and municipal solid wastes are also comprised a proficient feedstock for fuel production.

Biomass in Bangladesh

Biomass is considered as the prime source of energy in Bangladesh. Most of the rural and urban population use biomass resources for energy to meet their growing demand for energy for cooking, heating, and other purposes. The fraction of biomass used for various activities in Bangladesh is shown in Fig. 3 [26]. The sources of biomass in Bangladesh can be classified as 1) agricultural residue and waste, 2) municipal solid waste and 3) forest residue. The topical monsoon climate of Bangladesh is characterized by long, rainy, high temperature and humid summer but a short winter. The average temperature of the country varies from 21.2° C to 30.4° C with a relative humidity of 78%. The average rainfall varies from 1200 mm to 5800 mm [27]. Thus, the country has a favorable climate for biomass generation throughout the year.

However, due to rapid urbanization and industrialization trends of using commercial fossil fuels increased, whereas consumption of traditional biomass energy decreased rapidly, accelerating the GHG emissions [26,28,29]. If biomass can be converted into green and trouble-free source of energy trends of using biomass will increase, which will decrease pollution and GHG emissions. For example, production of hydrogen, synthetic gas, ethanol and biodiesel from biomass through gasification and other techniques. Currently, electricity generation from biomass resources has initiated in Bangladesh. This study evaluates the potency of hydrogen production from biomass and it also outlines a scenario of total biomass generation of Bangladesh. Various uses of biomass in Bangladesh are shown in Table 1.

Agricultural residues and wastes

Bangladesh utilizes around 64% of its total land area for agriculture [26]. Crop remnants that are usually left as it is after extraction or milling can potentially be used as biomass or as a source of energy. Paddy straw, rice husks, wheat straw

Table 2 – Estimates of annual agricultural crop production in Bangladesh (million ton).

Crops	2012–13	2013–14	2014–15	2015–16
Rice (total)	33.833	34.356	34.710	34.709
Wheat	1.255	1.303	1.348	1.348
Pulse (total)	0.265	0.320	0.378	0.378
Sugarcane	4.469	4.508	4.434	4.208
Jute	7.611	7.436	7.501	7.559
Maize	1.548	2.123	2.272	2.445
Coconut	0.326	0.347	0.384	0.374
Groundnut	0.126	0.056	0.057	0.062
Potato	8.603	8.950	9.254	9.474
Vegetable (total)	3.133	3.633	3.729	3.877
Cotton	0.028	0.020	0.030	0.033
Tea	0.063	0.067	0.066	0.065
Tobacco	0.079	0.085	0.094	0.088

Table 3 – Estimated generation, recovery rate and energy content of crop residue in Bangladesh [2015-16].

Residue type	Crop residue type	Residue production ratio		Residue production (million tons)	Estimated recovery (million tons)	Dampness present		The recoverable dry residue (million tons)	Lower calorific value		Energy potential (PJ)
		value	Ref.			%	Ref.		GJ/ton	Ref.	
Field residues	Rice straw	1.695	[38]	58.831	20.591	12.7	[38]	17.976	16.30	[38]	293.001
	Wheat straw	1.75	[39]	2.359	0.826	7.5	[35]	0.764	15.76	[35]	12.041
	Pulse residue[a]	1.9	[35]	0.718	0.251	20	[35]	0.201	12.80	[35]	2.573
	Sugarcane leaf	0.3	[39]	1.262	0.442	50	[40]	0.221	15.81	[39]	3.494
	Jute stalk	3	[39]	22.677	7.937	9.5	[35]	7.183	16.91	[35]	121.465
	Maize stalk	2	[39]	4.89	1.712	12	[35]	1.507	14.70	[35]	22.153
	Cotton stalk	2.755	[39]	0.091	0.032	12	[35]	0.028	16.40	[35]	0.459
	Groundnut straw	2.3	[39]	0.143	0.0501	12.1	[40]	0.044	17.58	[40]	0.774
	Vegetable residue[a]	0.4	[35]	1.551	0.543	20	[35]	0.434	13.00	[35]	5.642
	Potato[b]	0.4	–	3.790	1.33	20	–	1.064	13.00	–	13.832
	Subtotal			96.312	33.714			29.422			475.434
Process residues	Rice husk	0.267	[38]	9.267	9.267	12.4	[38]	8.118	16.30	[38]	132.323
	Rice bran	0.083	[38]	2.881	2.881	9	[35]	2.622	13.97	[39]	36.329
	Sugarcane Bagasse	0.29	[39]	1.220	1.220	49	[38]	0.622	18.10	[39]	11.258
	Maize cob	0.273	[39]	0.667	0.667	15	[35]	0.567	14.00	[35]	7.938
	Maize husk	0.2	[39]	0.489	0.489	11.1	[40]	0.435	17.27	[35]	7.512
	Coconut shell	0.12	[39]	0.045	0.045	8	[35]	0.041	18.53	[39]	0.760
	Coconut husk	0.41	[39]	0.153	0.153	11	[35]	0.136	18.53	[39]	2.520
	Groundnut husk	0.477	[39]	0.0296	0.0296	8.2	[40]	0.027	15.66	[40]	0.423
	Subtotal			14.752	14.752			12.568			199.063
Total				111.064	48.466			41.99			674.497

[a] Residues are assumed as field residues.

[b] Potato residue factors are considered same as vegetable.

coconut husks, and shell, mastered oil tree, bean, vegetable tree, jute, sugar cane bagasse and so forth are the major agricultural residues. A large amount of residue can be used as energy source and turn to energy and value-added product that might be waste and keep the bad impact on the environment.

Different crops contain different level of energy content that varies with moisture, species of crops and amount of bran mixed with husk etc. Fuel value and ash content are important factors that are the most essential to design the combustion or gasification system. The quality of biomass is also defined by the heating value of the biomass [19]. Agricultural biomass can ensure the requirements of the gasification system. Proximate and ultimate analyses show the presence of carbon, hydrogen, nitrogen, sulfur, moisture, and ash.

Being an agriculture based country; Bangladesh's economy is heavily dependent on various agricultural activities. 43% of the labor forces are employed to the agriculture and made the GDP more than 15% [30]. Crop cultivation and harvesting, and livestock production and farming are two major subclasses of agricultural activities. Biomass in the form of waste and residue received from these two subclasses are defined as agricultural crop residue, and animal manure and waste. The country produces a huge amount of biomass in the form of agricultural residue and waste where a large amount of that biomass can be used for power generation.

Agricultural crop residue. Rice, wheat, sugarcane, jute, potato, pulse, maize, cotton, coconut, groundnut, and vegetable etc. are the main harvesting crops of Bangladesh. Bangladesh experienced a cumulative increase in crop harvest. The country produced 19.32 million tons of total cereals in 1991–92 facial year increasing to 36.637 million tons in 2012–13 facial year. Finally, the total cereals production reached 37.153 million tons in the financial year 2015–16. The statistical estimation of agricultural crop production in Bangladesh is shown in Table 2 [31–34].

Crops production generates a large amount of residue which is the prime source of energy in rural areas. Residue production from various agricultural activities depends on total agricultural land and the number of crops. It is very difficult to measure the total crop residue generation as the proper data about residue generation is not obtainable. However, the statistical estimation of the residue generation is done depending on RPR (residue production ratio). A residue generation factor determines the ratio between the amount of the crop residue and the main product for each crop. Again, crop residues may be collected either during or after harvesting. According to the collection period, crop residues are classified as field residues and process residues. Generally, during harvesting field residues are not collected from the field to use them as fertilizer making a large portion of it unrecoverable [35]. Studies show that only 35% of the field residue can be recovered without adversely affecting the future yields [36]. On the other hand, 100% recovery rate can be achieved for processing residues of the crop [19]. Thus, the RRR (residue recovery ratio) has been speculated as 35% and 100% for process residues and field residues respectively [19,37]. Table 3 shows the estimated generation and recovery rates of crop residues in Bangladesh in FY 2015-16. Correspondingly, the estimated amount of net recoverable crop residue in Bangladesh in 2015–16 was about 111.062 million tons, among which the total recovery was 48.466 million tons as estimated. The table also shows that the recovered residues

Table 4 – Estimated number of livestock in Bangladesh (number of million heads).

Animal and poultry	2009–10	2010–11	2011–12	2012–13	2013–14	2014–15	2015–16	2016–17
Cattle	23.051	23.121	23.195	23.341	23.488	23.636	23.785	23.935
Buffalo	1.349	1.394	1.443	1.450	1.457	1.464	1.471	1.478
Goat	23.275	24.149	25.116	25.276	25.439	25.602	25.766	25.931
Sheep	2.977	3.002	3.082	3.143	3.206	3.270	3.335	3.401
Total animal	50.652	51.666	52.836	53.211	53.590	53.972	54.357	64.745
Chicken	228.035	234.686	242.866	249.010	255.311	261.770	268.393	275.183
Duck	42.677	44.120	45.700	47.253	48.861	50.522	52.240	54.016
Total poultry	270.712	278.806	288.566	296.264	304.172	312.293	320.633	329.200

Table 5 – Waste generation (manure and poultry dropping), recovery rate from livestock and its energy potential in FY 2016-17.

Livestock type	Dung yield		Million heads	Waste generation (tons/year)	Waste recovery (tons/year)	Dampness present		Recoverable dry waste (tons/year)	Lower calorific value		Energy potential (PJ)
	kg/animal/day	Ref				%	Ref		GJ/ton	Ref	
Cattle	5–10	[44]	23.935	65,522,062.5	–	–	–	–	–	–	–
Buffalo	8–12	[44]	1.478	5,394,700	–	–	–	–	–	–	–
Goat	0.25–0.5	[44]	25.931	3,549,305.63	–	–	–	–	–	–	–
Sheep	0.25–0.5	[44]	3.401	465,511.88	–	–	–	–	–	–	–
Total animal	–	–	64.745	74,931,580.01	44,958,948	40	[35]	26,975,368.8	13.86	[46]	373.88
Chicken	0.1	[44]	275.183	10,044,179.5	–	–	–	–	–	–	–
Duck	0.1	[44]	54.016	1,971,584	–	–	–	–	–	–	–
Total poultry	–	–	329.20	12,015,763.5	6,007,881.75	50	[35]	3,003,940.875	13.50	[45]	40.55
TOTAL			393.945	85,172,917.51	50,966,829.75			29,979,309.675			414.43

were 42.99 million tons without moisture, which energy content is equivalent to 674.497 PJ.

Animal manure and waste. Animal manure mainly consisted of an organic compound, wetness, and ash. It can be decomposed both in anaerobic and aerobic environments. Mainly, stabilized organic compounds and carbon dioxide is formed under aerobic environments. Whereas stabilized organic compounds, methane and carbon dioxide are formed under anaerobic environments [33,34]. Being an agricultural country, Bangladesh has a huge number of livestock and poultry. In the country, cattle, buffalo, goat, sheep, chicken, and duck are the prime resource of manure. In the rural areas of Bangladesh, animal manure is mainly used as cooking fuel and fertilizer. On the other hand, poultry droppings are used as fertilizer. Biomass power generation from manure and poultry dropping can be very effective to meet energy demand, especially in the remote areas. Thus, bad odder from manure and gas emissions during decomposition can be minimized. Table 4 presents that the estimated total number of livestock and poultry in Bangladesh was 270.712 million in the fiscal year 2009–10 that increased to 329.200 million in the fiscal year 2016–17 [41]. Manure generation (Dung yield) from animal depends on age, breed and feeding habits [35]. It is also influenced by the region and seasons [43]. The yield of dung was considered as 5–10 kg/animal/day for cattle, 8–12 kg/animal/day for Buffalo, 0.25–0.50 kg/animal/day for sheep and goat, 0.1 kg/animal/day for chicken and duck, [44]. Average value of the lower and higher dung yield was considered to estimate the annual manure and poultry dropping. Again, the recovery rate of manure and poultry dropping has been considered as 60% and 50% respectively [45,46]. Table 5 presents the production and recovery rate of manure and poultry dropping in Bangladesh in the fiscal year 2016–17. Accordingly, in the fiscal year 2016–17 manure and excreta generation from the animal was 74,931,580.01 tons and from poultry was 12,015,763.5 tons, totaling to 85,172,917.51 tons in a year and the estimated recovery was 50,966,829.75 tons, which is 59.839% of the total generation. It also shows that the total recovery of dry waste in 2012–2013 was approximately 29.98 million tons, as the considered dampness of animal waste is 40% and poultry droppings are 50% [35].

Municipal solid waste (MSW)

Wastes consisting of daily commodities like food scraps, product packaging, grass clippings, furniture, clothing, bottles and cans, newspapers, appliances, consumer electronics and waste parts are defined as municipal solid waste (MSW). It is also known as garbage or trash in different places around the world. Residential areas, institutions like schools and hospitals and commercial sources like restaurants and small businesses are the generation place of these wastes. MSW is a heterogeneous complex earth waste material. A property varies in a consistent way due to the inclusion of a number of wastes with different properties that change their physical, chemical and microbial properties. Special arrangements and conditions are required to know the physical and chemical properties of MSW whereas, the stability of MSW under the static or dynamic condition is important. To design an effective process and to utilize MSW biomass; stiffness, horizontal stress, unit weight, compressibility, shearing strength, and hydraulic conductivity etc. need to be considered. The composition of MSW varies based on place and time or area. The organic fraction of MSW is also one of the considerable factors to get the optimum amount of hydrogen and influence directly in production [42].

Municipal solid waste (MSW) is the mixture of various heterogeneous wastes that are inorganic and organic, slowly and rapidly biodegradable, fresh and stale, hazardous and nonhazardous, produced from urban areas because of various human actions [47]. MSW generation depends highly on socioeconomic conditions of a country. Due to the higher population growth rate, urbanization, industrialization and improved living standards increasing the rate of MSW

Table 6 – Contribution of various sources in MSW generation (2005) in Bangladesh.

Sources	Percentages of daily MSW generation						Average contribution
	Dhaka	Chittagong	Sylhet	Khulna	Rajshahi	Barisal	
Residential	75.9	83.8	78.0	85.9	77.2	79.6	78.1
Commercial	22.1	13.9	18.5	11.6	18.6	15.5	19.7
Institutional	1.2	1.1	1.3	1.0	1.2	1.5	1.2
Street sweeping	0.5	0.5	0.8	0.6	1.2	1.2	0.6
Others	0.4	0.6	1.4	1.0	1.8	2.3	0.5

Table 7 – Composition of MSW generated in major cities of Bangladesh.

Components of waste	Quantity in percentage						Average composition
	Dhaka	Chittagong	Sylhet	Khulna	Rajshahi	Barisal	
Organic matter	68.3	73.6	73.5	78.9	71.1	81.1	74.4
Paper	10.7	9.9	8.6	9.5	8.9	7.2	9.1
Plastic	4.3	2.8	3.5	3.1	4.0	3.5	3.5
Textile and wood	2.2	2.1	2.1	1.3	1.9	1.9	1.9
Rubber and leather	1.4	1.0	0.6	0.5	1.1	0.1	0.8
Metal	2.0	2.2	1.1	1.1	1.1	1.2	1.5
Glass	0.7	1.0	0.7	0.5	1.1	0.5	0.8
Other	10.4	7.4	9.9	5.1	10.8	4.5	8.0

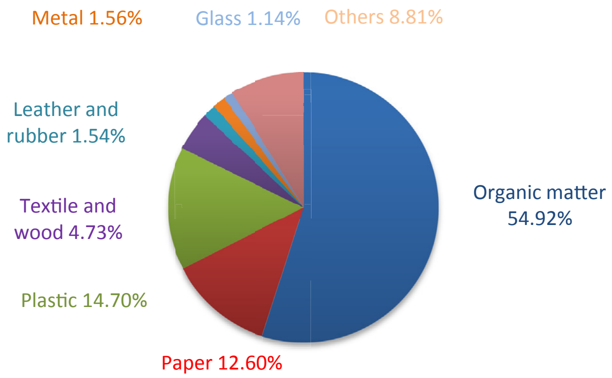

Fig. 4 – Average composition of MSW.

generation is the common scenario of every Asian city. World Bank estimated that the growth of MSW generation in the world will increase from 1.2 kg/capita/day to 1.42 kg/capita/day in the coming fifteen years [48]. Like other developing countries, Bangladesh is suffering from various environmental and other problems because of the massive amount of MSW generation and its mismanagement [49].

This indicates the high presence of biodegradable materials in the MSW. Comparing the waste composition found in Dhaka in 2005 and in 2013, a difference is evident. It is because of the per capita waste generation and the average waste composition changes with a change in lifestyle and income level. Table 6 demonstrates the contribution of various sources in MSW generation in six major cities and the average contribution of various sources in the total waste generation of the country [50].

Table 7 presents the percentages of various components making MSW in six main cities of Bangladesh in 2005 [50].

The major constituents of MSW include organic matter, plastic, paper, wood, leather, textile, rubber, metal, and glass. Fig. 4 shows the average composition of MSW found in the capital Dhaka of the country. To get the average composition waste from twenty different places were analyzed [51]. Accordingly, the percentage of organic matter is high in the MSW. The composition of MSW content found in other major cities of the country has very little variation [50]. As MSW generated in the country has high organic content, it is suitable for power production throw technologies like gasification, incineration and landfill methane capture etc. To utilize this mountainous amount of MSW generated in the country some actions have been taken recently. Proper management of this huge amount of MSW will contribute to meet the country's power demand and will save our environment.

Bangladesh's estimated population was 162.951 million with a population density of 1252 p/km^2 in 2016. Among them, 34.9% (approximately 56,856,665 people) live in urban areas and the rest 65.1% (approximately 106,094,895 people) live in rural areas [52]. The per capita west generation is so different in the urban and rural areas because of the difference in living standards and industrializations. Studies found that the per capita waste generation of the country in the city and village areas is about 0.41 kg/capita/day and 0.15 kg/capita/day respectively [19,53]. Again, the collection or recovery rate is also found very different in various studies ranging from 44 to 100% due to lack of standards. The study considers the recovery rate of municipal solid waste is about 70% [50,54]. Considering the data above, total generation and recovery of country's MSW in 2016 has been estimated by summation of multiplying the respective generation rate to respective total population and considering 70% recovery. Table 8 shows that the total generation and recovery of MSW were 14.318 million tons and 10.022 million tons respectively in Bangladesh in 2016. It also revealed that the dry mass of the recovered waste was 5.512 million tons which energy content is 102.303 PJ.

Forest residue

According to the Asian development report 2016, Bangladesh having 11.2% of the forest area of the total of the country which is not enough for country need. Moreover, Bangladesh losing its forest due to the rapid population growth, accommodating 8–10 lacs Rohingays in Taknaf and coxsbazar region and for industrialization. Maximum tress is used in sawmill of urban areas and wood processing industries. The forest residues are sawlogs, pulpwood, twigs, and leaves. The rural population of the country depends heavily on the forest for fuel and other products. The forest sector accounts for about 3% of the country's GDP and 2% of the labor force. Thus, a large amount of fuelwood and forest residue as categories of biomass is generated in the country. Bangladesh has an estimated forest land of 2.6 million hectares which is almost 17.4% [55]. Table 9 shows the amount of forest land distributed in different districts of Bangladesh [32].

The state-owned forests are eccentrically distributed in the country. 12 Districts in the eastern and south-western regions of the country hold about 90% of the state-owned forest land and 32 districts out of 64 districts have no state-owned forest [32]. The world's average per capita forest area is 0.60 ha, whereas in Bangladesh it is less than 0.015 ha [56]. 84% of the total forest area has been classified as natural forest and nearly 16% as plantation forest. The two most common types of forest, namely Hill forest and Mangrove forest cover more

Table 8 – Estimated generation and recovery of MSW in Bangladesh in 2016.

Area	Generation per capita		Waste generation (million tons/year)	Waste recovery (million tons/year)	Dampness present		Recoverable dry waste (million tons/year)	Lower caloric value		Energy potential (PJ)
	kg/capita/day	Ref			%	Ref		GJ/ton	Ref	
Urban	0.41	[50]	8.509	5.956	45	[20]	3.276	18.56	[20]	60.803
Rural	0.15	[20]	5.809	4.066	45	[20]	2.236	18.56	[20]	41.500
Total			14.318	10.022			5.512			102.30

Table 9 – District wise forest land in Bangladesh in 2015–16.

District name	Un-classed state forest (acre)	Forest land under forest department (acre)	Total forest land (acre)
Dhaka		934.47	934.47
Gazipur		65,173.21	65,173.21
Mymenshing		38,860.14	38,860.14
Jamalpur		10,364.39	10,364.39
Sherpur		20,087.10	20,087.10
Netrokona		1975.59	1975.59
Tangail		122,876.90	122,876.90
Sylhet	988.88	49,439.48	50,428.36
Hobigonj	2200	34,160.73	36,360.73
Maulavibazar	1079.41	70,314.32	71,393.73
Sunamgonj		18,012.31	18,012.31
Chittagong		426,089.18	426,089.18
Cox's Bazar		209,216.49	209,216.49
Bandarban	494,372.54	303,168.95	797,541.49
Rangamati	763,890.54	614,673.59	1,378,564.13
Khagrachari	454,077.95	100,038.26	554,116.21
Camilla		1720.92	1720.92
Feni		20,191.43	20,191.43
Bagerhat		566,512.95	566,512.95
Khulna		546,081.61	546,081.61
Satkhira		370,357.18	370,357.18
Rangpur		3449.04	3449.04
Nilphamari		1200.08	1200.08
Kurigram		128.59	128.59
Lalmonirhat		82.62	82.62
Dinajpur		18,065.14	18,065.14
Thakurgaon		1591.68	1591.68
Panchagar		4550.87	4550.87
Noagaon		7147.64	7147.64
Noakhali		384,784.72	384,784.72
Lakshmipur		50,000.00	50,000.00
Patuakhali		150,000.00	150,000.00
Barguna		75,000.00	75,000.00
Perojpur		6000.00	6000.00
Bhola		360,000.00	360,000.00
Total (Acre)			63,688,590.17
Total (Million hectors)			2.57,938,796

Table 10 – Forests of Bangladesh and their main products.

Forest type	Location	Area (million hectares)	Major products
Hill forest	Sylhet, Habiganj, Chittagong and Cox's Bazar	0.67	Large sawlog, poles, firewood, thatching material and bamboo
Natural mangrove (Sundarban)	Khulan, Bagerhat,and Satkhira	0.60	Timber, poles, firewood, pulpwood and thatching material
Mangrove afforestation	Along the coastal zone of the country	0.19	firewood, pulpwood
Sal forest	Gazipur, Tangail, Comilla, Sherpur, Mymensingh, Dinajpur, Rangpur, Thakurgaon, Naogaon and Panchagarh	0.12	poles, posts, and firewood
Un-classed state forest	Hill Tract districts	0.73	bamboo, thatching material, and firewood
Swamp Forest	Sylhet and Sunamganj	0.02	support to freshwater fisheries and are vital spawning grounds
Village forest	Scattered throughout the country mostly on the homestead land	0.27	timber, bamboo, poles, posts, and firewood

Table 11 – Wood processing residue generation in Bangladesh.

Wood processing type	product's quantity		Residue generation (million tons)
	1000m3	million tons	
Veneer log and saw log and	174	0.099	0.099
Industrial round wood split and plywood	91	0.052	0.052
Particleboard, round, split and pulpwood	14	0.007	0.0007
Total	279	0.158	0.1517

Table 12 – Forest residue estimation in Bangladesh.

Residue type	Residue generation (million tons)	Residue recovery (million tons)	Dampness present		Dry residue (million tons)	Lower calorific value		Energy potential (PJ)
			%	Ref.		GJ/ton	Ref.	
Fuel wood	15.111	15.111	20	[38]	12.089	15.00	[19]	181.335
Tree residue[a]	1.821	1.821			1.821	12.52	[59]	22.799
Processing residue	0.1517	0.1517	20	[38]	0.1214	18.00	[19]	2.185
Total	17.084	17.084			14.031			206.319

[a] Tree residues are considered moisture free.

Table 13 – Biomass potential of Bangladesh.

Biomass type		Generation of biomass (million tons)	Recoverable biomass (million tons)	Dry mass (million tons)	Energy potential (pet joule)	Coal equivalent (million tons)
Agricultural residues	Crops	111.064	48.466	41.99	674.497	23.028
	Animals	85.173	50.967	29.980	414.43	14.149
MSW		14.318	10.022	5.512	102.303	3.493
Forest residues		17.084	17.084	14.031	206.319	7.044
Total		227.639	126.539	91.513	1397.549	47.714

than 68% of total forest area. Table 10 presents the types of forest found in Bangladesh and their major products.

Forest remnants and waste wood are vital sources of energy [55]. Forest residues mainly consist of wood fuel, tree residues, and wood processing remnants. Veneer logs and saw logs making, plywood and particleboard industry, fuelwood and pulpwood are the common sources of wood biomass, which is mainly used as firewood. The generation rate of residues depends on tree species and methods of processing. Whereas, the recovery rate is considered as 100% [19]. Saw-mills and plywood industries produce almost the same amount of residues to their wood products and 10% residue production has been considered for particle board industries [40,57]. Thus, we can estimate the wood processing

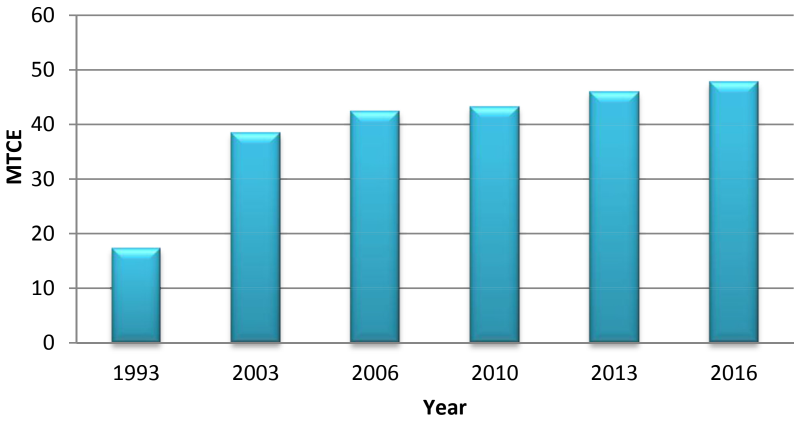

Fig. 5 – The energy potential of biomass in Bangladesh.

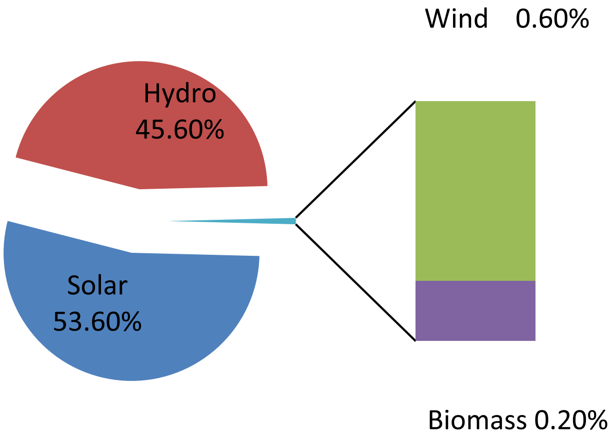

Fig. 6 – Renewable energy for power generation in Bangladesh [55].

residue production in Bangladesh considering the mass density is 0.57 ton/meter^3. Table 11 shows the wood residue production in the country in the fiscal year of 2015–16 [58].

However, fuelwood is the main source of forest biomass in the country, followed by three residues. In the fiscal year 2015–16 total wood fuel production was 26,511 m^3 or 15.111 million tons [58]. The plant remnants (leaves, twigs, roots, and bark) production was evaluated as 1.821 million tons in 1992 [59]. Due to unavailability of information about fuelwood, the study considers the information of wood processing residue and plant remnants production in 2015–16 in the country to estimate the total forest residue potential of Bangladesh in 2015–16. Table 12 shows the generation, recovery and energy content of forest residue biomass in the country. Accordingly, the estimated recoverable forest residue generation of Bangladesh was 17.084 million tons in FY 2015-16 which is equal to 14.031 million tons of dry biomass and its energy potential is about 206.319 PJ.

Prospect of biomass in Bangladesh

As a source of energy, biomass has many advantages like a lower price, low sulfur content and ability to renew [54]. But it has some drawbacks; like decentralized resource, low unit thermal output, high moisture contents, massive volume, environmental issues and collection and storage problems [26]. Having a large population and being an agricultural country Bangladesh produces a large amount of biomass in various forms. Considering the data from Tables 3, 5, 8 and 12 the total biomass generation, recovery and its potential in Bangladesh in 2016 can be estimated. Table 13 presents the overall biomass potential of Bangladesh in 2016. Accordingly, in the year 2016 the total recoverable biomass generation was 126. 539 million tons in the country that has dry mass was 91.513 million tons and is equivalent to 47.714 million tons of coal. Though Bangladesh generates huge amount of biomass from various resources, but a large portion of it is not utilized and left in open places causing critical environmental and health problems. Fig. 5 presents the cumulative increment in biomass generation in the country. In 2003 the total quantity of recoverable biomass was estimated at 74.128 million tons identical to 38.41 MTCE (million tons coal equivalent) [19]. The

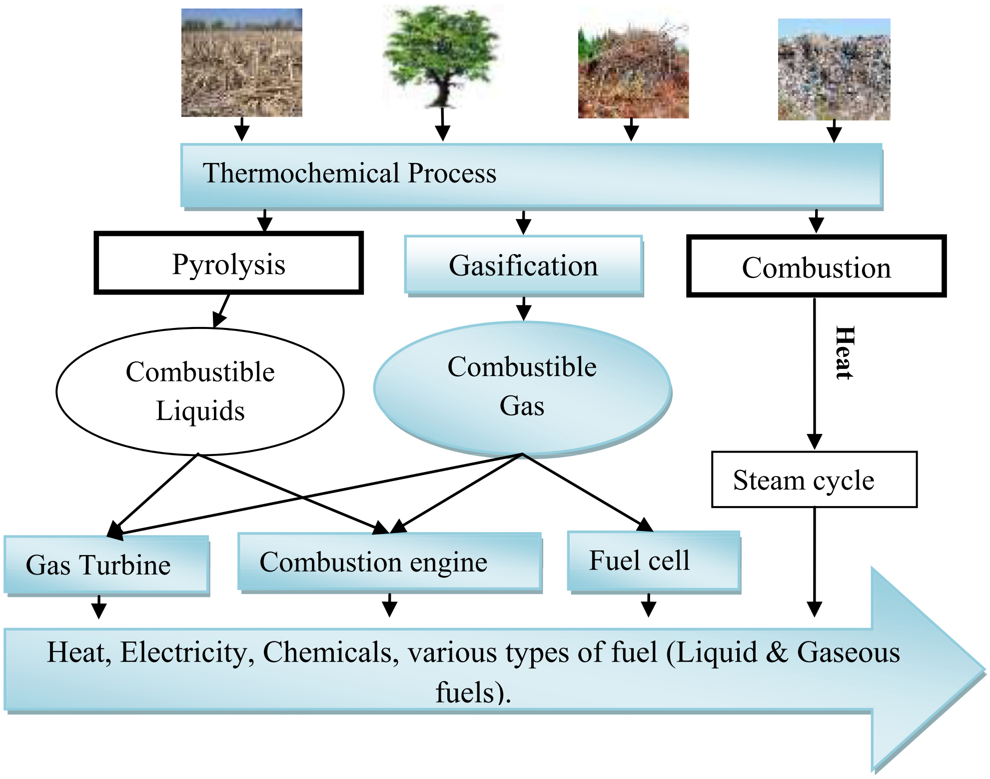

Fig. 7 – Thermochemical conversion routes of biomass and possible end-use application.

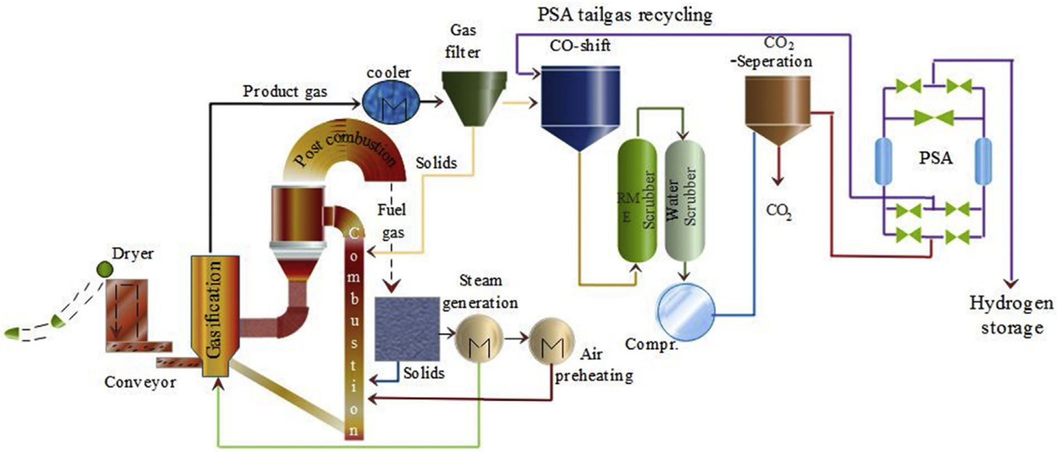

Fig. 8 – Process flow diagram of biomass to hydrogen.

amount increased to 42.45 MTCE in 2006 and finally reached to 47.71 MTCE in 2016. If this huge amount of biomass is utilized properly, a burden will turn into an asset and contribute to meet our energy demand.

Recently, Bangladesh has started using biomass for power generation. Examples are, two biomass (rice husk) based gasification and power generation plant at Gazipur and Thakurgaon respectively and a proposed MSW to energy conversion pilot project at Keraniganj [59,60]. Fig. 6 presents the renewable energy share of biomass for power generation in Bangladesh. In Bangladesh, the utilization of biomass (e.g. MSW) is not satisfactory and it should be scaled up as soon as possible.

So, the balanced merger among local conditions, proper measures of potentiality, use of best possible technology and technical program and development of new energy conversion methods by doping advanced technologies can make effective and efficient use of biomass resources for the country to meet its power demand and to prevent environmental pollution.

Biomass to hydrogen conversion routes

Biomass can be typically converted to 'Bioenergy or Hydrogen' by the biochemical process and thermochemical process. The review highlight the production of hydrogen (clean renewable energy) from biomass by thermal conversion methods. Biomass is transmuted to energy via a thermochemical process including the imputation of viscose process along with heat. There are a number of possible routes in thermochemical conversion of renewable feedstock to useful fuels and chemicals.

Thermal conversion of biomass includes mainly three methods – pyrolysis, gasification, and combustion. Various types of solid, liquid or gaseous fuels can be produced from different biomass resources such agro residual waste, municipal solid waste (MSW), forest residual waste etc. It also includes the production of heat [59]. Fig. 7 illustrates the thermo-chemical conversion of biomass in different possible ways that have different end products. Gasification process produces gases with syngas that could be one of the sources of hydrogen. Thermal decomposition of biomass in an oxygen restricted environment refers to the pyrolysis process. With the addition of heat the biomass breaks down to condensable vapours, non-condensable gases (pyrolysis gas), and charcoal [61]. The condensable vapours form a liquid known as bio-oil or pyrolysis liquid, which contains a wide range of oxygenated chemicals and water. Again, biomass gasification process is the conversion by partial oxidation i.e. more oxidizing agent than for pyrolysis but less than for complete combustion at high temperature of biomass which indicates that the product of gasification process is gas while that of pyrolysis is liquid whereas combustion, another thermochemical process produces heat. Use of this combustion product for running steam cycle contributes to the production of heat, electricity, various types of liquid fuels. Fig. 7 shows thermochemical conversion routes of biomass and possible end-use application. A great degree of researches has been carried out on thermal chemical conversion processes, among them gasification is mostly being used commercially in all over the world (Fig. 8).

Gasification technologies

A standard process flow diagram helps to illustrate whole hydrogen production process from biomass. A well-established plant design of process flow in Gussing, Austria is considered as a reference to detail out the system step by step. Here, Gasification process refers to the conversion of organic or carbonaceous feedstock which includes high temperature [61] and mainly produces gaseous products including hydrogen (H_2), carbon monoxide (CO), abbreviate amount of carbon dioxide (CO_2), nitrogen (N_2), water (H_2O) and higher hydrocarbon (C+). Controlled amount of air, steam or coalescence of the components are being used as gasifying agents. Reaction between carbon monoxide and water for the production of hydrogen is commonly known as water-gas shift reaction. Different types of scrubber (such as RME scrubber, water scrubber) ascertain the cleaning and drying. Then segregation of CO_2 ensues in special membrane

Table 14 – Gasification technologies & process conditions [66–70].

Operational Condition	Name of the gasifier				
	Updraft Gasifier	Downdraft Gasifier	Bubbling Fluidized Bed	Circulating Fluidized Bed	Entrained Flow Bed
Fuel specifications	Less than 51 mm	Less than 51 mm	Less than 6 mm	Less than 6 mm	Less than 15 mm
Approvable amount of moisture in the product gas.	60%	25%	<55%	<55%	<15%
LHV of gas	5–6 MJ/Nm^3	4.5–5.0 MJ/Nm^3	3.7–8.4 MJ/Nm^3	4.5–13 MJ/Nm^3	4–6 MJ/Nm^3
Reaction temperature		1090 °C	800–1000 °C		1990 °C
Ash and other particulates in the product gas	Elevated	Meager	Elevated	Elevated	Meager
Gas exit temperature	200–400 °C	700 °C	800–1000 °C		>1260 °C
Tar	30–150 g/Nm^3	0.015–3.0 g/Nm^3	3.7–61.9 g/Nm^3	4–20 g/Nm^3	0.01–4 g/Nm^3
The potency of hot gas	90–95%	85–90%	89%	89%	80%
Residence period	Particles stay in bed until its complete infusion		Particles stay in bed for long period.	Particles often pass through the bed.	Very short (few seconds)
Ash melting point	>1000 °C	>1250 °C	>1000 °C		>1250 °C
carbon conversion efficiency	Higher	Higher	Higher but the aggravation of carbon in ash is noticed.	Higher	Higher
Process flexibility		Very determinate. Design of gasifier is dependent on process variables.	More pliable to loads than design		Very determinate. Range of size and energy content is strictly maintained.
Temperature profile		High	Mostly constant in case of vertical gasifier design and shows slight radial variation.	Almost constant in case of vertical gasifier design.	Temperature is higher than the ash melting temperature.

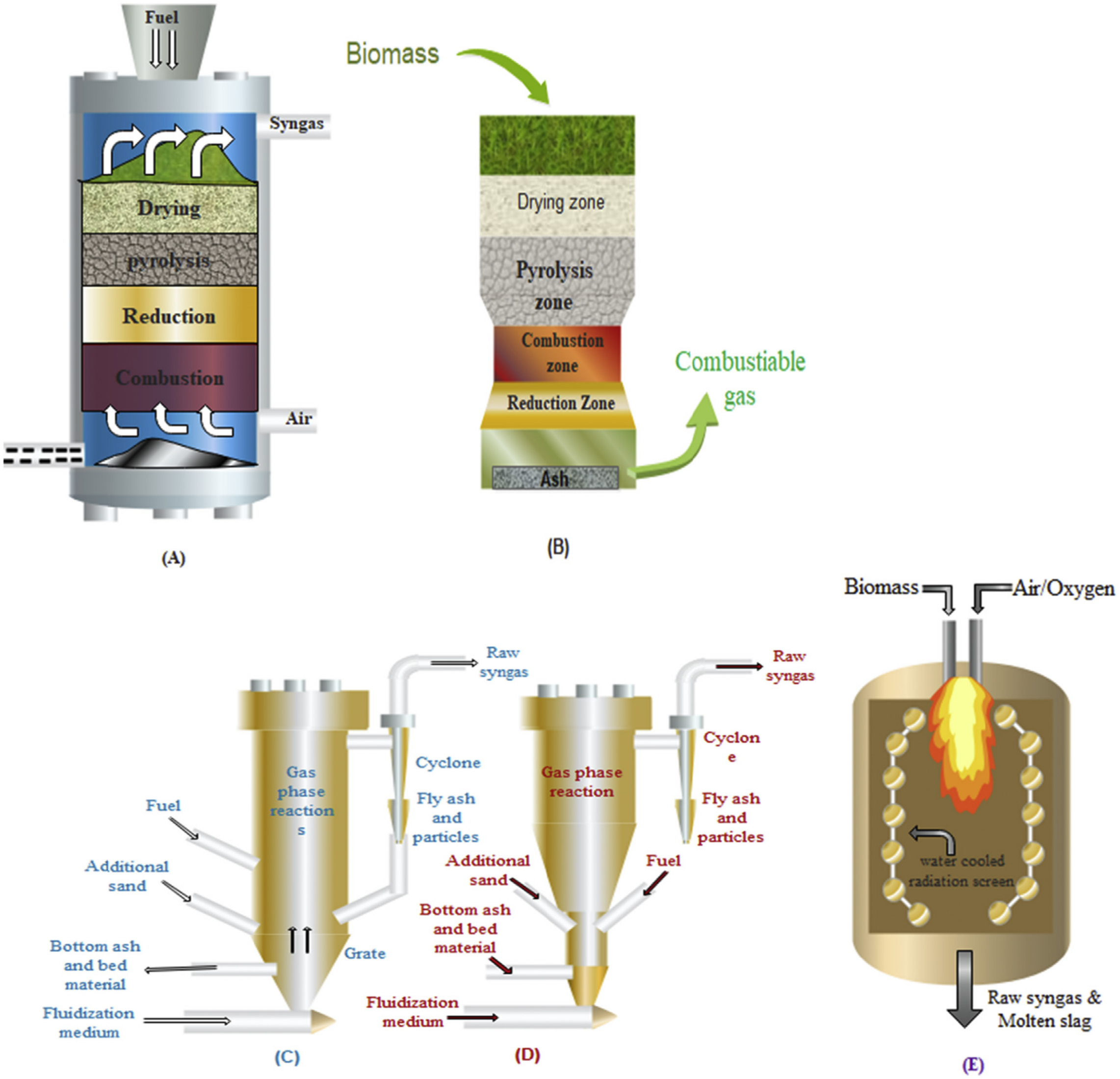

Fig. 9 – Schematic diagram of (A) Updraft gasifier [65] (B) Downdraft gasifier [64] (C) Bubbling bed gasifier [65] (D) Circulating bed Gasifier [65] (E) Entrained flow gasifier.

separation unit (Fig. 8). From pressure swing adsorption (PSA) of the product gas delivers the final sanctified hydrogen gas. This sanctified hydrogen is stored and sent to end users.

Biomass gasification methods

Gasification methods are largely dependent on the density factor which refers to the ratio of solid matter that a reactor can anneal to the total volume available [62]. Density factor may divide gasification methods into two types such as **dense phase reactors** in which feedstock materials occupy the maximum space of the reactor and the other is **lean phase reactors** which include one large reactor chamber for stimulating the reactions of drying zone, a combustion zone, pyrolysis zone, and reduction zone [62,63]. These gasifiers may be further classified into different sub-groups. **Fixed bed gasifiers** (Downdraft gasifier and updraft gasifier) are known as dense phase reactor whereas lean phase reactor includes fluidized bed gasifiers of two types such as bubbling fluidized bed gasifier & circulating bed gasifier and entrained flow gasifiers. Bellow 51 mm is the allowable dimension of feed particle size for Updraft and downdraft gasifier, whereas bubbling fluidized bed and circulating fluidized bed allows less than 6 mm and less than 15 mm particle size is allowed in case of entrained flow bed gasifier. Fluidized bed gasifier approves less than 55% moisture content in feedstock whereas that is 25%, 60% and less than 15% in case of downdraft, updraft and entrained flow bed gasifier respectively. The LHV of a gas range of updraft gasifier is 5–6 MJ/Nm^3 which is higher than that of downdraft gasifier. Still, the LHV of gas of circulating fluidized bed (4.5–13 MJ/Nm^3) is relatively higher than all another gasifier. A large amount of tar formation in updraft gasifier makes it less efficient. Amount of ash and various particulate contents in the fuel gas obtained from updraft gasifier, bubbling gasifier and circulating fluidized bed gasifier is relatively higher than that of downdraft gasifier and entrained flow bed gasifier. There are noticeable variations in the temperature profile of the gasifier. Reaction temperature also has some significant impacts on the performance of the gasifier. Table 14 shows all the prominent characteristics and their approvable range for different gasification methods. Fig. 9 represents the diagram of different gasifiers [64,65]. Fixed bed gasifiers are proven and simple reactor with low investment cost whereas fluidized bed reactors require high investment cost which is proven with coal. Additionally, the construction of entrained flow gasifier is complex.

Pros and cons of different gasification methods

Different types of gasification methods have already been discussed in former affiliation based on their prominent characteristics. Pros and cons of a method enhance their acceptability. Both Updraft and downdraft gasifier is simply designed with proven technology. The thermal conversion efficiency of downdraft gasifier is high [71] but its CO and H_2 production capability are comparatively low. High carbon conversion efficiency is appreciable in case of downdraft gasifier. Again higher conversion of biomass with low tar and unconverted carbon is residue in fluidized bed gasifier. Updraft gasifier allows the gasification of feedstock material having a low moisture content [72]. Besides updraft gasifier can process the feedstock material containing higher moisture content and inorganic contents. Entrained flow gasifier has greater flexibility to the feedstock material [71,73]. Though any form of feedstock like dry or slurry can be used, penetration of water from slurry reduces the thermal conversion efficiency [72,74]. Size of feed particle plays absolute partitioning role among various gasifiers [73,75]. Entrained flow gasifier requires extremely reduced size particle [71] and feedstock size is also strictly needed to be maintained in case of other gasifiers such as circulating fluidized bed accepts only attenuated solid feedstock within the dimension range 100 mm. Updraft gasifier has a small aptitude for slag formation [72] but it has high sensitivity to tar content in syngas so it requires extensive syngas cleanup. Downdraft gasifier is less sensitive to the Char and Tar content of fuel [72]; hence, it accepts materials with different characteristics. Fluidized bed reactor, as well as entrained flow reactor produces mixture gas containing a reduced amount of char, tar, and CO_2 [71]. Temperature shows diverse impacts on gasifier of different characteristics [75]. Downdraft gasifier has a great temperature controlling efficiency. The relatively low process temperature is needed to be maintained in bubbling bed gasifier to fudge defluidization of the bed. On the other hand in entrained flow gasifier high temperature and pressure of the process activate high throughput and rapid feed conversion [72]. Loss of carbon with ash and ash slagging also affects the performance of entrained flow gasifier [71,74]. The same trend has also been found in case of bubbling fluidized bed gasifier. The investment cost of updraft gasifier is low whereas that of the fluidized gasifier and entrained flow gasifier is very high. Again fixed bed gasifier has easy operation system [71] whereas that of the fluidized bed and entrained flow gasifier is very complex [71]. Efficiency and effectiveness of gasifier or gasification method are associated with the pros and cons of the process which also act as indicative property in determining the technical and economic viability of the method.

Current enhancement strategies of gasification technologies

Advanced new concepts of gasification process aim at the flourishment of utilization of biomass gasification process include integration of gasification and gas cleaning technologies (UNIQUE gasifier), pyrolysis combined with gasification and combustion, plasma gasification, supercritical water gasification, multi-staged gasification etc [76,77]. Research on integration and combination of processes has been able to attain the attention of the researchers as a way of increased syngas yield with better quality and maximum purity, increased the efficiency of the overall process and improved economic viability by decreasing investment cost [76,78]. UNIQUE gasifier concept comprises the integration of gasification of feedstock, fuel gas cleaning and conditioning in only one reactor unit at reduced investment cost [77]. This strategy may also be termed adventure on of gasification and gas cleanup in an identical reactor. Fennell et al. [76] reported this method as an effectual process on the basis of lab testing result. In multi-stage gasification concept; a single controlled stage is employed for the separation and combination of gasification and pyrolysis. Though this process increases the process efficiency with high-quality syngas and minimum tar content, a combination of two processes enhances complexity [71]. Multi-stage gasification process aiming at the scanty production uses gasification and partial oxidation stage in combined [77]. Another new concept is the integration of distributed pyrolysis plants with central gasification plant which can be used for gasifying low-grade biomass. Heidenreichet al. [77] stated indirect biomass co-filing in coal-fired boilers as an economical way to reduce fossil CO_2 emission. Polygeneration-combined heat and power; combined SNG, heat and power; combined biofuels, heat and power; combined hydrogen and heat enhance many fold efficiency of gasification process [76,77] but it poses some process design complexity. The main advantageous properties of thermal plasma gasification are that its temperature profile is high; it poses high intensity and non-ionising radiation [78]. However, higher energy density also makes this process more efficient. The extremely higher temperature of this process makes it highly compatible with gasification process and it can gasify feedstock material containing high moisture content irrespective of size and structure. But high power requirement makes this process less efficient [76]. Biomass containing higher moisture content and liquid biomass can be treated by supercritical water gasification method [76,77]. Supercritical gasification has high solid conversion efficiency (more than 99%) and the product gas contain a high concentration of hydrogen gas (up 50%) with the suppression of formation of char and tar. Along with water; some catalysts also have a significant impact on the reactions of the process. This process requires high investment cost. FT process coupled with gasifier produces clean and carbon neutral biofuels [76]. Development of advanced catalysts may enhance the sorption enhanced reforming and biomass gasification with CO_2 capture [76]. Following Table 15

Table 15 – -Strategies of gasification enhancement technologies [72,78].

Strategies/ Concepts	Features	Advantages	Current state	Limitations
UNIQUE gasifier [72,78]	Integration of gasification of feedstock, fuel gas cleaning and conditioning only in a reactor unit.	1) Robust technology. 2) attenuated investment costs	Mainly being used in testing at lab-scale.	Further research may enhance its competence for large-scale production.
Multi-stage gasification concept [72,78]	The accomplishment of pyrolysis as well as gasification in a separate reaction by an individual controlling system.	1) Improve process efficiency 2) High-quality product gas with a minimal amount of tar.	Implementation of the strategy from 100 kW to 6 MW gave significant output.	Enhanced complexity as a result of combining two reactors.
Integration of distributed pyrolysis plants with a central gasification plant [72,78]	Large centralized gasification plant contributes to the gasification of oil-char slurries obtained from distributed pyrolysis plant for producing biofuels.	1) Can gasify distributed, low-grade biomass 2) Economic transportation cost of the biomass as well as biofuel	Being used in demonstration plant of 5 MW.	This process cannot be used for the economic production of gasoline and olefins.
Combination of gasification with a partial oxidation stage [78]	Gasification stage and partial oxidation stage proceeds combinedly.	1) Reduced amount of tar content	Multi-stage gasification processes use this for scanty production.	Restricted to large-scale application.
Indirect biomass co-filing in coal fired boilers [78]	Product gas of gasification stage is co-fired with coal.	1) Simple operation system. 2) Can diminish CO_2 emissions from fossil economically.	Bing used massively	
Polygeneration-combined heat and power [78]	Combined heat and power production.	1) Enhanced process efficiency.	Used in small scale.	Only decentralized energy production is possible because heat needs to be produced near the consumer
Polygeneration e combined SNG, Heat, and power [72,78]	Generates syngas, heat, and power combinedly.	1) Exalted process efficiency and flexibility. 2) Generation of renewable transportation fuel	Realization of the process is in small-scale whereas large-scale encampment is being designed.	Penurity of a natural gas distribution system increases the costing of the process.
Polygeneration-combined bio-fuels, heat, and power [78]	Simultaneous generation of biofuels, heat, and power.	1) Exalted process efficiency and flexibility. 2) Generation of renewable transportation fuel	Realization of the The process is in small-scale whereas large-scale encampment is being designed.	Complex process design and non-economic where natural gas distribution system doesn't exist.
Poly-generation-combined hydrogen and heat [72,78]	Contemporaneous generation of hydrogen and heat	1) Higher overall process competency. 2) Origination of renewable hydrogen.	Being used in a smaller scale.	Enhanced complexity in process design
Plasma gasification [72,78]	Gasification of biomass feedstock includes the use of plasma.	1) Treatment of hazardous waste 2) Morbidity of any organic material into its elemental particles.	Mainly used for waste treatment	Exalted investment cost and power requirement; Downcast process efficiency.
Supercritical water gasification [72,78]	Supercritical water is used for gasifying feedstock material.	1) Biomass with higher moisture content and liquid biomass can be treated 2) Does not require any pre-treatment of feedstock.	Lab-scale testing and research	Requires higher energy content requirement along with higher costing.

(continued on next page)

Table 15 – (continued)

Strategies/ Concepts	Features	Advantages	Current state	Limitations
FT process coupled with a gasifier [72]	FT-fuels synthesis exerts the product gas obtained from gasification process.	Clean, carbon-neutral liquid biofuels are produced.		Intricate process design.
Sorption enhanced reforming and biomass gasification with CO2 capture [72]	Presence of catalyst and sorbent is a must in gasification of feedstock t.	1) Augment production of H_2. 2) Wanted amount of tar.		Requires advanced research on catalysts cum sorbents.

Table 16 – Significant investigation on gasification technologies.

References	Area of investigation
Tyagi et al., 2017 [65]	Technological advances and upliftment of gasification technologies had been reviewed. It also highlighted the obstacles in the proclamation of these technologies as well suggested some provision for making the technology exoteric and adjuvant for the society.
Fennell et al., 2016 [72]	Different areas of biomass gasification system as environmentally favorable and sustainable technology had been focused.
Chianeseet al, 2016 [64]	Status of biomass gasifiers, their advantageous and disadvantageous properties and implementation of the biomass gasification system had been reviewed.
Heidenreich et al, 2015 [91]	Reviewed the newer strategies for integration and combination of the processes for improving process competency with excellent pure gas quality at lower investment cost.
Samiran et al, 2014 [88]	Several forms of palms like empty fruit bunch (EFB), oil palm frond (OPF) and palm kernel shell (PKS) as an effective feedstock material for producing synthesis gas had been reviewed and the high heating value was reported.
Chhitiet al, 2013 [86]	Thermal cracking or catalytic conversion of producer gas into synthesis gas by thermochemical process had been investigated and stated entrained flow gasifier as an apposite technology for gasification at high temperature.
Modiet al, 2013 [85]	Performance and upliftment of downdraft gasifier and several niceties in optimizing the parameters of the system had been reviewed.
Trninic et al, 2012 [93]	Gasification of biomass with the production of CHP and exertion for making the process economic had been reviewed.
Beohar et al., 2012 [80]	The contribution of the gasifier in terms of equivalence ratio, temperature, producer gas composition, cold gas efficiency, calorific value and rate of gas production had been evaluated.
Sastry et al, 2011 [81]	Different investigations and improved prospects of downdraft gasifier on the basis of technological advances and impacts of various factors on the composition of product gas had been presented.
Siedlecki et al., 2011 [83]	Production of fuel gas followed by the implication of liquid fuels through the Fischer-Tropsch process in a fluidized bed gasifier had been reviewed.
Upadhyay et al, 2011 [81]	Various perspectives on proximate-ultimate analysis, equivalence ratio and particle size, the heating value of fuel, fuel consumption and syngas composition obtained from a downdraft gasifier of 10 KW had been reviewed.
Pipatmanomai, 2011 [87]	Based on technical and economic prospects utilization of biomass and condition of biomass conversion technologies had been discussed.
Surjosatyo et al, 2010 [/92]	Various alternations in gasifier for reducing tar in gasification and different mechanisms of tar morbidity had been reviewed.
Arnavat et al, 2010 [90]	The idea of different gasification models based on thermodynamic equilibrium, kinetic, and artificial neural networks had been explored.
Kumar et al., 2009 [80]	Production of chemicals, bio-fuels, and bio-power by thermochemical process had been reviewed.
Weller et al., 2008 [79]	Current progress and troublesome issues of the gasification process of biomass had been reviewed; Utilization of syngas had also been highlighted.
Jain et al., 2007 [72]	Promotion and exploration prospects of fixed bed gasification alongside different commercial appliance had been proposed.

summarizes common feature, advantages, current state and limitations of these newer gasification technologies.

A brief feature of biomass gasification process

Gasification of biomass is considered as the most convenient and economic method for the production of Hydrogen. Hydrogen is environment-friendly fuel compared to the conventional fuel. Continuous research and development work is being enacted all over the world. In earlier studies, Chopra et al. (2007) [79] and Wang et al. (2008) [80]reviewed on different aspects of gasification technology (Such-fixed bed gasification) and advances of biomass gasification techniques. Wang et al. (2008) [80] also focused on the troublesome issues of utilization of product gas or syngas. Kumar et al. (2009) [81] reviewed on the gasification of biomass via thermochemical methods for producing chemicals alongside bio-power and bio-fuels. Biomass gasification technologies play a very conscious role in achieving the optimum gasification condition and outcomes. The review by Bhavanam et al. (2011) [82] and Upadhyay (2011) [83] on downdraft gasifier and parameters that influence the gasification process whereas Siedlecki et al. (2011) [84] focused on fluidized technology for biomass gasification process in his review. Beohar et al. (2012) [85] also reported same. Kureshiet al. (2013) [86] reviewed the execution and upliftment of downdraft gasifier and reported various **niceties** in optimizing process parameters whereas Chhiti et al. (2013) [87] et al., mentioned that entrained flow gasifier as an apposite technology for high-temperature gasification. On the contrary, Pipatmanomai (2011) [88] speculated the overall biomass conversion technologies and their economic aspects. Samiran et al. (2014) [64] reviewed oil palm frond (OPF), empty fruit bunch (EFB), and palm kernel shell (PKS) as different potential biomass feedstock material for gasification and identified high heating value of syngas. Fennell et al. (2016) [76] focused on the variant areas of biomass gasification. Along with the gasification technologies, Molino et al. (2016) [89] evaluated advantages and disadvantages of gasifiers. Molino et al. [89]; also reviewed the application of the technologies and the potential use of syngas. Reduction of tar content in product gas contributed to the promotion of efficiency of the gasifier. Mechanisms of tar morbidity were reviewed by Surjosatyo et al.; (2010) [90] on the basis of various modifications in gasifiers. Arnavat MP et al. (2010) [69] explored the idea of different gasification models based on thermodynamic equilibrium, kinetic, and artificial neural networks. Heidenreich et al. (2015) [77] stated that enhanced process competency with excellent pure gas quality at low investment cost could be enabled by the integration and combination of the process. Recent studies of Tyagi et al. (2017) [91] stated the technical advancements and developments in biomass gasification technologies. It also reviewed the difficulties in disseminating biomass gasification over conventional technologies. This review paper focused on the various biomass feedstock (such as agricultural residue, municipal solid waste and forest residue), factors influencing the performances of gasification technology and various downstream pathways for producing hydrogen. Table 16 comprises the summery of research objectives of many researchers regarding gasification technologies.

Conditional effects of the gasification process

A critical review revealed that the performance of biomass gasification depends on various factors. Factors or parameters listed below have a significant influence on the production of producer gas whereas the ultimate goal is to produce pure hydrogen. Moreover, should count the quality, efficiency, sustainability etc. of the system. According to Radwan et al. [75] and fennell et al. [76] the most common influencing factors are the size of feedstock particle, moisture content, heating rate, temperature, pressure, steam-to-biomass ratio, equivalence ratio, Bed material, gasifying agents, Catalysts.

Li et al. (2009) [92] studied gasification of palm shell, fiber, and empty fruit bunch of particle size ranging from 0.15 to 5 mm in a fixed bed gasifier in the presence of a tri-metallic catalyst at temperature ranging between 750°C-900 °C; reported that when the temperature increased from 750 °C to 900 °C maximum value of total gas yield (2.48 m^3/Kg) and hydrogen gas yield (1.481 m^3/Kg) were achieved. With the increase in temperature, the concentration of H_2 and CO_2 augmented whereas the concentration of CO and CH_4 abated. Besides, when the particle size increased from 0.15 to 5 mm there is a curtailed yield of total gas yield and hydrogen gas i.e. small particle size contributes to higher production of H_2 and CO_2 with lower CH_4, CO, C_2H_4 production. Another study mohammed et al. (2011) [93] investigated gasification empty fruit bunches the temperature range between 700 and 1000 °C using inert sand as bed material in fluidized bed gasifier; noted that an increase the concentration of H_2 (10.27–38.02 vol%), CO and CH_4 (5.84–14.72 vol%)while the concentration of CO_2 decreased with the increase in temperature. At 1000 °C the total gas yield increasingly reached to the maximum value of 92 wt%. Impact of particle size also followed the same trend as Li et al. [92] stated. Feng et al. [94] reported an increase in temperature from 700 °C to 900 °C contributes to an increment of H_2content notably from 23.35% (V) to 51.02% (V); also noted the increase of CO_2content from 20.96% (V) to 27.35% (V) on the contrary CO content diminished from 35.6 2% (V) to 20.13% (V) and gas output raised from 0.19 m^3/kg to 0.83 m^3/kg. In this experiment, it was also reported that when the particle size of pine sawdust increases below from 0.125 mm to 0.250 mm, feeding rate decreases resulting decrease amount of H_2 and CO content in product gas composition while CO_2 and CH_4 content increases. Hernández et al. [95] stated that with the reduction of particle size (8 mm–0.5 mm) fuel conversion efficiency increases from 57.5% to 91.4%. A recent research demonstrated by Kumar et al. (2016) [96], pilot scale fluidized bed at the temperature ranges between 650 and 950 °C found that increase in temperature positively influences the formation of H_2, N_2, O_2, and CO along with the increased CH_4 reforming. Further increase in temperature promotes the conversion of H_2 into CO and H_2O by reverse water gas shift reaction. Pressure has a direct influence on the performance of gasification process. Gasification rate of char increases with the increasing pressure [75]. According to Kumar et al. [96]

increased pressure of gasifier includes the reduction of partial pressure of CO and CH_4 along with the increase in CO_2, H_2 and O. Liu et al. (2016) [97]carried out his experiment in a fluidized bed gasifier at 700 °C temperature and pressure ranging between 0.1–5 Mpa, concluded that with the increasing pressure of gasification process H_2 and CO contents in product gas composition decreases while CO_2 and CH_4 contents increases. Experimental result of Kumar et al. (2016) [96] indicated that increased pressure of the reactor is responsible for the increased concentration of H_2, N_2, O_2, and CO. He also emphasized on the decreased concentration of CH_4 and CO_2. According to Fennell et al. [76], it can be concluded that biomass containing moisture more than 30% significantly influences gasification temperature which results in less production of final product. In the very earlier studies of Gray et al. [98], it has been reported that increased moisture content decreases the temperature of the gasifier. Besides steam to biomass ratio is considered to have a robust influence on input energy requirement and composition of product gas [76]. Wongsiriamnuay et al. (2013) [98] reported that increased steam to biomass ratio resulted in an increase in yield of H_2, CO_2 gas but the reduction in CO, CH_4, and heating value. Additionally, research report by Li et al.(2009) [92]concluded that when the SB was increased from 0 to 1, H_2 gas composition increased significantly from 13.50 vol% to 18.56 vol%. However, with the further maximization of SB ratio from 1 to 1.5, it started to reduce. High ER value decreases the production of H_2 significantly, while increases the CO_2 output purposely. The overall study of Huang et al. [97], Mohammed et al. [93] and Kumar et al. [97] conceive that increasing equivalence ratio value increases the volume fraction of H_2 and CO but it is responsible for the low-quality gas mixture with low concentration of H_2 and CO. Again increased equivalence ratio act as aiding factor in case of producing gas mixture with low char and tar content [76]. According to Kumar et al. (2016) [96] increasing equivalence ratio (0.20–0.50) promotes over-oxidation and partial combustion of synthesis gas. Again fundamental concept obtained from different studies is that bed materials act as reaction shifting factor by removing CO_2. As a result, increases H_2 yield. Research result of Wongsiriamnuay et al. [98]indicated that product gas containing highest H_2 contents, highest LHV and CCE (%) could be produced by maintaining catalyst to biomass ratio 1.5:1 where silica sand was employed as bed material. Various gasifying agents like air, steam, oxygen, SCWG etc. also poses high impact on the end product of the gasification process. Wongsiriamnuay et al. (2013) [98]used air-steam as gasifying agent instead of air and reported an efficient gas yield and CCE (%) of the process. Chang et al. (2011) [99]reported the maximize bio-hydrogen and CO yield could be obtained at 1000 °C without using steam whereas concentration of CO_2 is 10.9% only. Unlike other influencing factor catalysts don't affect the total gas yield but it greatly influence the composition of product gas. Many researchers have been carried out on Ni-based and Zn-based materials, alkaline metal, dolomites and limestones, alumina and zeolites [76]. Amid those alkaline metal oxides, Ni-based catalysts and dolomite showed advantageous effects on gasification process by promoting reformation reaction [100]. Some other foreign and sparse metals like platinum- and ruthenium-based materials also show positive influence on gasification process. Catalysts are chosen based on their effectiveness for instance Ni-based catalysts are more feasible for the transmutation of light hydrocarbons while Alumina silicates enhance the gasification of char effectively [76]. Impacts of various parameters on the performance of gasification system are summarized in the following Table 17 based on the experimental data and research results of the researchers.

Biomass gasification derived product gas to hydrogen

Thermal gasification of biomass produces gas which is known as product gas and tars are separated. This gas composition is mainly CO and H_2 along with the minor amount of CO_2, H_2S, N_2, CH_4, H_2O tar etc also called producer gas, wood gas, syngas, or synthesis gas [102,103]. It is derived from biomass, coal or other hydrocarbons through gasification as well as other thermal operations. Some contents present in this gas are considered as impurities during its utilization [104]. Common impurities are organic compounds known as tar, fine particulates, sulfur-containing compounds, hydrogen halides, nitrogen-based compounds and trace metals. The composition of product gas is varied with feed types, production methods, operation conditions etc [102]. Gasification methods and compositional details of produce gas are mentioned in previous sections. According to the BioH2 production from biomass gasification plant in Güssing, Austria [105], the product gas composition is shown in Fig. 10.

There are few advanced technologies to separate hydrogen from the product gas. The study focuses only general separation technique that enhances the level of hydrogen contents (>99%) as fuel or source of energy [106,107]. To obtained high pure hydrogen, the product gas is treated through several steps. Mainly, there are four types of additional operations like (1) Water Gas Shift (WGS) with suitable catalyst (2) Scrubber for drying and cleaning (3) Membrane separation (MS) (4) Pressure swing adsorption (PSA).

A Sankey diagram with a proportional molar fraction of components is given below (Fig. 11):

The change of a portion of gas content is demonstrated by the width of the color bar in Sankey diagram. Particles are removed by bag-house filter [108]. To increase hydrogen content in the gas mixture, widely accepted steps are mentioned above.

Water-gas shift (WGS) process

In this the process, CO is converted to H_2 via the reaction between steam and CO at different conditions. Common exothermic reversible reaction during water-gas shift process is as following [109–113]:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad \Delta H = -41.1\ \mathrm{kJ\ mol^{-1}}$$

The content of CO is turned down through WGS process to avoid the early damage of PEMFC during operation [114]. Very recently, WGS process with gasification has got much popularity in the production of hydrogen from biomass [115–117]. In general, the temperature range in gasification coupled with

Table 17 – Conditional effects on the performance of gasifier.

Researchers	Operational condition & system configuration	Effects on the performance of gasifier							
		Feedstock particle size	Temperature	Pressure	Steam to biomass ratio	Equivalence ratio	Bed Material	Gasifying agent	Catalysts
Kumar et al. (2016) [75]	GT: pilot scale fluidized bed H: 1400 mm ID: 108 mm F: Coconut shell FS: 70–500 μm FR: 5–20 kg/h P: 1–5 Mpa BT: 650–950 °C ER: 0.20–0.50	Small particle size improves gas quality and increases overall energy efficiency but increases the expenditure of gasification plant and devolatilization time.	Higher temperature enhances the formation of H_2, N_2, O_2, and CO along with the increased CH_4 reforming.	Increase in the pressure of reactor there is an increase in the concentration of H_2, N_2, $O_{2,}$ and CO while CH_4 and CO_2 decreased.	–	Higher ER value results in a low quality gas mixture with a lower concentration of H_2 and CO.	–	–	–
Liu et al. (2016) [98]	GT: fluidized bed gasifier F: Rice husk FR: 1 kg/h ER: 0.22–0.48 AR: 1.38 kg/h BT: 700 °C P: 0.1–5 Mpa	–	Gasification efficiency and gas yield gradually increased with the increasing temperature.	With the increasing pressure of gasification process H_2 and CO contents in product gas composition decreases while CO_2 and CH_4	–	–	–	–	–
Wongsiriamnuay et al. (2013) [99]	GT: fluidized bed H: 2000 mm ID: 50 mm F: bamboo FR: 0.6 kg/h FS: 0.10–0.25 mm BM: silica sand C: dolomite GA: air/Steam ER:0.4 SB: 0:1 and 1:1 BT:400,500,600 °C	–	When the temperature increased from 400 °C to 600 °C; concentration of H_2 and CO decreased, on the contrary, the concentration of CO_2 increased.	–	Augmentation in S/B ratio results in an increment in the yield ofH_2, CO_2gas but a retrenchment in heating value and CO, CH_4 content.	Higher equivalence ratio increases the reactivity of char, results ina decrease in H_2, CO content at a higher temperature.	Maximum H_2 content, Highest LHV, and highest CCE (%) can be obtained at C/B: 1.5:1.	H_2, CO, and CH_4 contents in the fuel gas were high when an air/steam mixture is applied.	H2 and CO content increased with increasing catalysts to biomass ratio while CH_4 and CO_2 content slightly decreased.
Yin et al. (2012) [102]	GT: Downdraft gasifier F: Peach prunings FS: < 1 cm AR: 20 m^3/h GR: 27.8 ± 2.6 m^3/h BI: 3 kg ER: 0.58 ± 0.02 HP: 1.3 ± 0.2 min Duration of gas production: 14.9 ± 0.4 min Total time: 16.3 ± 0.5 min	When the size of the particle increases from below 1 cm –8 cm, gas yield increases while the tar and dust contents decrease as much as possible.	–	–	–	The consumption rate of biomass decreases with the increase in ER value.	–	–	–

(continued on next page)

Table 17 – (*continued*)

Researchers	Operational condition & system configuration	Effects on the performance of gasifier							
		Feedstock particle size	Temperature	Pressure	Steam to biomass ratio	Equivalence ratio	Bed Material	Gasifying agent	Catalysts
Feng et al. (2011) [95]	GT: Fixed bed F: pine sawdust FS: 0.125 mm P: atmospheric C: dolomite BT: 700,750,800,850, 900 °C	An increase in feed particle size decreases the feeding rate and increases residence time. It also results in a decrease in CO and H_2 content.	Increase in temperature favored increased yield of H_2 and dry gas while LHV (KJ/kg) decreased.						The increased amount of H2 and dry gas yield with low LHV was observed when dolomite was used as a catalyst.
Chang et al. (2011) [100]	GT: fluidized bed ID: 63.9 mm H: 1100 mm F: α-cellulose (moisture content 2–10%) FS: <0.35 mm GA: air–steam ER: 0.27 SB: 0, 0.5, 1, 1.5 BT: 600–1000 °C	–	–	–	Higher S/B ratio contributes to the low LHV value.	When ER value 0.2 at 1000°C temperature is used the maximal yield of the bio-hydrogen and CO can be obtained.	–	Maximum yield of the bio-hydrogen and CO can be obtained at 1000 °C without using steam whereas the concentration of CO_2 is 10.9% only.	–
Mohammed et al. (2011) [94]	GT: fluidized bed L: 600 mm ID: 40 mm F: EFB (<10 wt% moisture content) FR: 0.6 kg/h FS: 0.3–0.5 mm BM: inert sand GA: air ER:0.15, 0.20, 0.25,0.30, 0.35 BT: 700–1000 °C		With the increasing temperature, the overall gas yield also increases.			Very higher ER value is responsible for the lower concentration of H_2 and CO in the product gas.	Inerts can be used as a good heating medium.		
Hernández et al. (2010) [96]	GT: Entrained flow gasifier. F: De-alcoholisedmarc of grape. FS: 0.5 mm BT: 1050 °C P: 3 bar F/A ratio: 4.25 FR: 1.49 kg/h AR: 2.04 kg/h FC: 1.36%	Small particle size is responsible for the increase in the concentration of combustible gases and a slight decrease in the concentration of CO_2	–	–	–	–	–	–	–

Li et al. (2009) [93]	GT: Fixed bed gasifier ID: 200 mm; 88 mm (catalytic reactor) H: 400 mm; 1200 mm (catalytic reactor) F: palm oil wastes (shell, fiber, and EFB) FR: 0.3 kg/h FS: 0.15–2 mm BM: tri-metallic catalyst GA: steam SB: 0, 0.67, 1.33, 2,2.67 BT: 800 °C	LHV value is promoted by the increased particle size whereas large particle size results in low production of H_2 and CO_2.	Increased temperature of the catalytic reactor resulted in the increased amount of H_2 and CO_2,while those of the other gases such as CO, $CH_4$and C_2 hydrocarbon were decreased.	–	Increased S/B ratio contributes to the increase in total gas and H_2 yield to a certain limit after that the yield start decreasing.	–	By using nanoNiLaFe/γ-Al2O3 maximum yield of gas mixture of optimum gas composition along with maximum H_2 yield can be obtained	Steam is responsible for increasing H_2 and CO_2 composition in the product gas.	Greater activity for tar cracking in vapor and of hydrocarbons was found to result a higher hydrogen yield.

Here, GT: gasifier types, H: gasifier height, ID: gasifier internal diameter L: gasifier length, F: feedstock, FS: feed stock size, BT: bed temperature, GA: gasifying agent, BM: bed material, FR: feed rate, SB: steam to biomass ratio, ER: equivalence ratio, CCE: carbon conversion efficiency, C: Catalysts.

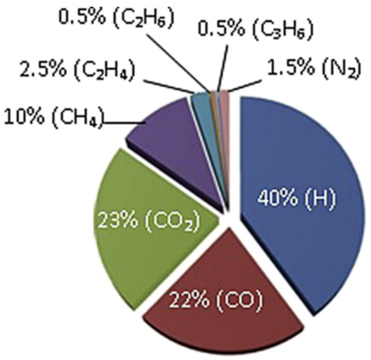

Fig. 10 – Composition (on volume basis) of product gas derived from biomass gasification [105].

WGS is 600⁰C–1000 °C whereas the presence of oxygen/air and/or steam as gasification agent [118,119] with different catalysts.

In the WGS process, the increment of hydrogen content and significant CO conversion highly varied with different catalysts as well as reaction condition [120–123]. Numerous articles regarding the effect of catalysts demonstrated the promising result as shown in Table 18. An industrial scale study of the production of Biohydrogen from producer gas using Double Fluidized Bed reactor for biomass gasification was conducted and WGS result is as Fig. 12 [105]. Kaftan A. et al. [121]; found the increased selectivity to CO_2 on the KOH modified catalyst. Miao D-K et al.; [124], Izquierdo U. et al.; [120], Kaftan A et al.; [121], Viktor J. Cybulskis et al. [123]; worked on the Pt-based catalyst and got a satisfactory result [Table 18]. Catalytic deactivation also revealed by couple investigation [120,124–126]. M. Kraussler et al. observed no catalytic deactivation at 200 h of operation and obtain CO conversion up to 93% [127] while SimeoneChianese et al. found 83% CO conversion using same catalyst [128] (Table 19).

Tang et al. (2015) modified iron base catalyst with Cr and CaO for maximum 96.40% CO conversion at operating temperature range 350° C–450° C [129]. Copper with CeO_2 deposited on foam was used in the experiment of Charlotte Lang et al. (2017) in fixed bed reactor at 300 °C –500 °C temperature. 81.40% CO conversion was the output of their experiment [130]. An optimum combination of catalyst and system conditions will be considered as a blessing in the world of fuel technology. A tentative conversion of CO and enhancement of H_2 content can be assumed from Fig. 12 [105].

Cleaning and drying using scrubber

Further treatment is needed to separate tar, water, ammonia and some organic compounds present in the gas mixture after WGS process. Wood gas or product gas or producer gas drying and cleaning are a primary and most influential step. After gasification, the product gas is cool nearly ambient temperature to run the further processes like bag house filter and scrubbing with RME, water and glycol etc. [105,108,127]. Tar, NH_3, steam, and other particulates along with

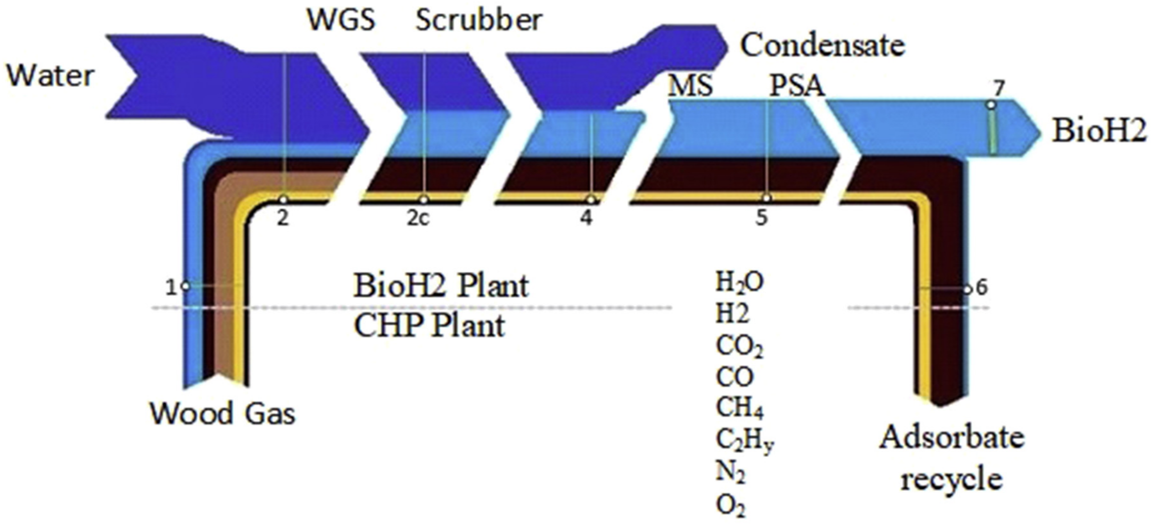

Fig. 11 – Sankey diagram showing molar fraction of component [155].

Table 18 – Different WGS processes and performances.

Reactor	Catalyst/reactor	Temperature	Efficiency	Ref.
Fixed-bed quartz tube reactor	Platinum/strontium apatite	673	95% CO conversion	Dengyun Miao et al. (2017)
Micro-channel heat exchanger reactor	2.9%Pt-1.4%Re 2s micro-channel heat-exchanger reactor	370	85% CO conversion	U. Izquierdo et al. (2017)
High-Temperature Reaction Chamber	KOH-coated Pt/Al_2O_3	Above 280 °C	Increased CO conversion	Andre Kaftan et al. (2017)
Not Available	Sodium on Pt/Al_2O_3	250 °C	Nearly all CO conversion	Viktor J. Cybulskis et al. (2016)
Three fixed bed reactors	Iron–Chromium	320 °C –440 °C	63 g H_2 per kg biomass, up to 93% CO conversion	M. Kraussler et al. (2016)
Fixed-bed quartz tube reactor	CaO/Fe–Cr	250 °C –550 °C	96.40% CO conversion	Tang et al. (2015)
Fixed-bed reactors	Iron–Chromium	350 °C –450 °C	83% CO conversion	SimeoneChianese et al. (2015)
Fixed-bed reactors	5.5 wt %Cu and 9.0 wt %CeO_2	300 °C –500 °C	81.40% CO conversion	Charlotte Lang et al. (2017)

temperature are significantly reduced by RME scrubbing method [127].

J. Loipersbock et al. observed a significant reduction of Ammonia (99.7%), benzene, toluene, xylene (Tar, BTX, 70%), water (3–5%) and sulfur (70%) by two-stage biodiesel Scrubber maintaining the temperature at 10–30 °C in the first stage and 3–10 °C in the second stage [108]. Some articles focused on tar removal with different scrubbing agents like bio-oil, activated carbon, char etc. Bio-oil scrubber with char and activated carbon showed 60% tar reduction at 3 ± 1 °C, while only bio-oil scrubber showed higher efficiency (64.5%) at 50 °C [131,132]. But the combination of bio-oil scrubber with char bed filter gave an outstanding performance (98%) in tar reduction 50 °C [132]. It is clear that tar reduction is a temperature dependent process and presence of additional filter can significantly improve the reduction efficiency. SiriwatUnyaphan et al. [133] developed a highly efficient (90%) and low-cost venturi scrubber with canola oil to compare with that of bubbling scrubber and found 18% more tar removal efficiency [134]. Another experimental result of same authors revealed the improved tar removal efficiency [132] of 97.70% of gravimetric tar removal by increasing absorption surface area of micro-bubbles produced by gas and proposed maximum 99.20% tar removal by combining cyclone, ceramic filter, air cooler, water coolers venturi scrubber and packed bed absorber consecutively. Also, no naphthalene and phenol are reported [133].

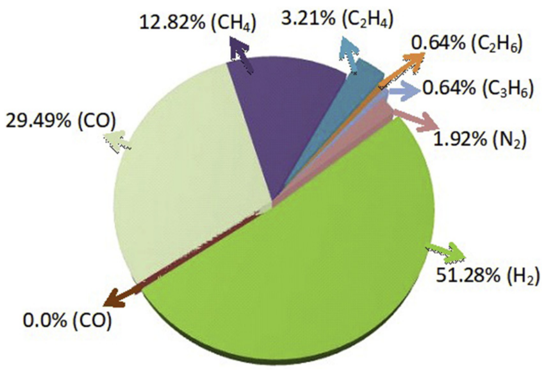

Fig. 12 – Product gas composition after WGS process [105].

Table 19 – Different Scrubbing processes and performances.

Methods	Particulates removed (Performance)	Ref
Biodiesel scrubber with two-stage cooling system	BTX (Tar, 70%) Sulfur (70%) Water (3–5%) Ammonia (99.7%),	J. Loipersbock et al. (2017)
Bio-oil Scrubber with, Char and activated carbon bed, 3 ± 1 °C	Tar (60%)	Shunsuke Nakamura et al. (2015)
Bio-oil Scrubber, 50 °C	Tar (64.5%)	Shunsuke Nakamura et al. (2016)
Bio-oil Scrubber with Char bed, 50 °C	Tar (98%)	Shunsuke Nakamura et al. (2016)
Venturi scrubber with oil absorbent	Tar (more than 90%)	SiriwatUnyaphan et al. (2017)
Venturi oil scrubber	Tar (Overall 87.10%)	SiriwatUnyaphan et al. (2017)
Scrubber with a Fe-activated carbon bed	Tar (95.79%) Sulfur and Other particles (91.93%)	Toshiaki Hanaoka et al. (2012)
Wet packed bed scrubber	Up to 75% tar and dust cleaning	A.G. Bhave et al. (2008)
Oil scrubber with Dolomite bed, 50 °C	Tar (Overall 97%)	V. Pallozzi et al. (2018)
Waste cooking oil and waste char bed scrubber	Tar (80.6%) Naphthalene (95%)	Thanyawan Tarnpradab et al. (2016)
Scrubber with Collected waste palm cooking oil (CWPCO)	Tar (86%)	Nor Azlina Ahmad et al. (2016)
Scrubber with CWPCO with activated carbon	Tar (98%)	Nor Azlina Ahmad et al. (2016)

Toshiaki Hanaoka et al. [135]; demonstrated 95.79% tar as well as 91.93% sulfur and other particles reduction by scrubber with Fe-supported activated carbon bed. Wet packed bed scrubber was prepared with water and sand of different particle size [136] and Tar and dust cleaning efficiency were gained up to 75%. Product gas from biomass gasification was passed through a combined configuration of gas conditioning and cleaning section and the obtained almost 100% reduction of tar of heavier aromatic hydrocarbons and 90% for others except benzene (>55%) at 50 °C [136]. The absorbance of high hydrocarbon tar by waste cooking oil and lower hydrocarbon tar by waste char, respectively, were observed with waste cooking oil and waste char bed scrubber. Tar (80.6%) and Naphthalene (95%) reduction were found in a study [128] and connection of the WC bed after the WCO scrubber resulted into 3.1% increment of tar removal efficiency of WCO scrubber.

The tar reduction performance of collected waste palm cooking oil and collected waste palm cooking oil with activated carbon in scrubber is compared [137,138]. The result cleared out that the collected waste palm cooking oil with activated carbon is a better choice [139].

Membrane separation

Several techniques can be applied to optimize the H_2 recovery from biomass-derived producer gas via gasification. These techniques are followed by some other advanced methods like membrane separation [140]. It provides a high purity of hydrogen in the gas mixture at low cost and effectively and 3 mm thick metallic membrane with Zeolitic-imidazolate framework-8 at temperature 200 °C modest performance on hydrogen separation from biomass derived gas [142]. Different catalyst based membrane is developed to optimize the membrane performance. Pd based catalysts are an excellent choice but its cost is very high and that's why different Pd alloy is being developed to compensate the cost without compromising performance [141–144]. Producer gas is passed through the membrane at different conditions. Selective gas can pass through the membrane to allowed side driven by chemical potential. Different types of membranes are used presented in Table 20 [145].

A study [146] showed that 4 microns ceramic based Pd–Ag membrane at 400 temperatures and 100 kPa for 900 h gives a high H_2 permeance ($\int 4 \times 10^{-6}$ mol m^{-2} s^{-1} Pa^{-1}). A similar study was carried out by Ref. [147]. At first, Monsanto developed commercial polymeric membrane to recover hydrogen in the 1980s [148] and its application is widening rapidly for hydrogen recovery from biomass processing for the use in proton exchange membrane fuel cell [149]. Table 21 demonstrates the application of different polymeric membrane [150]. Aleksander Makaruk et al. [150] used glassy polymer membrane to separate hydrogen from syngas derived by biomass gasification. Details of membrane development were discussed by Torsten Brinkmann and Sergey Shishatskiy [151].

Table 20 – Different membranes for hydrogen separation (Partial pressure difference is a common driven force for all types of membranes) [141].

Membrane type	Typical composition	Parameters				
		Temperature	Mechanism	Permeability	Cost	Selectivity
Polymeric	Polyimide; cellulose acetate	110 °C	Solution-diffusion	Low-moderate	Low	Moderate
Metallic	Palladium; Palladium alloys	150–700 °C	Solution diffusion	Low	Moderate-high	Very high
Microporous	Silica; Zeolites; Metal-organic frameworks	1000 °C	Molecular Sieving	Moderate-high	Low-Moderate	Low-moderate

Table 21 – Polymeric membrane for H_2 separation.

Materials & Types	Selectivity			Reference
	H_2/CO	H_2/CH_4	H_2/N_2	
Cellulose Acetate (Spiral wound)	21	26	33	[165]
Polyimide (Hollow fiber)	30	–	35.4	[159]
Polyimide/Polyaramide (Hollow fiber)	–	–	–	[153]
Polysulfone (Hollow fiber)	23	24	39	[147]

Pressure swing adsorption (PSA)

After reforming and CO processing, the hydrogen content in syngas increase significantly. The present syngas is rich in hydrogen but further purification is necessary as CO causes the deactivation of the catalyst of the proton exchange membrane fuel cell (PEMFC) electrode [152]. Different pressure swing adsorption systems on the basis of adsorption size, velocity, regeneration, and choice of the adsorbent material are designed for better performance. Edy Herianto Majlan et al. [107] studied the performance of compact pressure swing adsorption (CPSA) with activated carbon as the adsorbate. Average hydrogen purity was 99.99% in 60 cycles at 0.04 kg H_2/kg adsorbent with purge/feed ratio was 0.001 and vent loss/feed ratio was 0.02. Aca Jovanovic et al. [101] conducted an experiment for pure hydrogen from biomass-based gasification in Güssing, Austria and results are shown in Figs. 13, 14.

A plant scale operation to obtain pure hydrogen from the wood gas of steam gasification was carried out maintaining the following optimum conditions (Table 22) and available impurities present in obtained results Fig. 15 [153]. Both figures Figs. 15 and 16, shows that impurities level, is lower (below 1%, Fig. 15) [104] than that (above 45%, Fig. 14) of [107] and Figs. 14 and 16 demonstrate the comparative volumetric results of PSA process [105,159] (Table 23).

Besides hydrogen purification from biomass-based product gas, some works on separation of hydrogen from syngas were also done by researchers. Moon D-k et al. [106]; found the H_2 purity of 99.77–99.95% and recovery 79% on two layered bed with activated carbon and activated carbon-Zeolite at 34° C to 36 °C and 25–35 bar maintain purge and feed ratio of 0.05–0.1. In case of four layered bed, production purity, as well as recovery rate was improved but the farther improvement of P/F

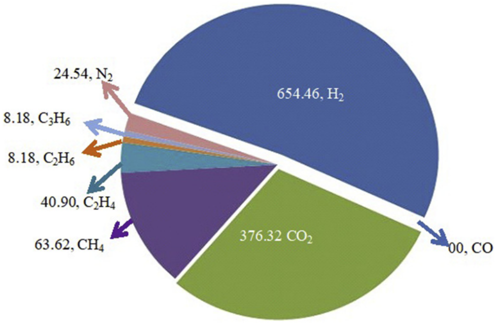

Fig. 13 – Flow (on volume basis, Nm^3/h) of gas on the inlet of PSA [105].

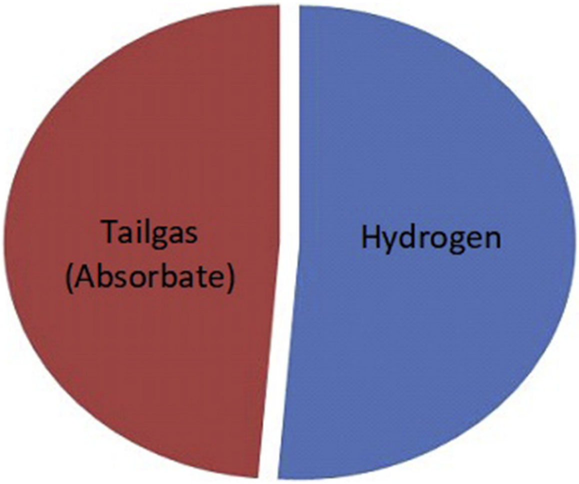

Fig. 14 – Flow of hydrogen on the out let of PSA [105].

Table 22 – Operating conditions of PSA.

Parameter	Value (unit)
Adsorption pressure	6.5 bara
Desorption pressure	0.1 bara
Purge/feed time ration	5×10^{-3}
Feed flow rate	0.7 ± 0.04 (m^3_{ndb})/h
Feed pressure	1000 ± 17 mbara
Adsorption time per column	650 s
Equalization pressure	4.5 bara

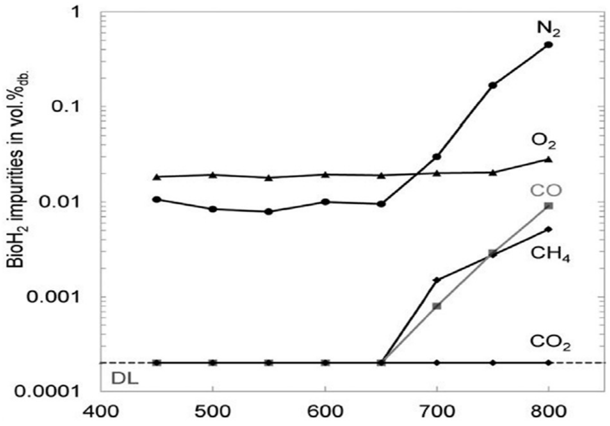

Fig. 15 – PSA results with bio hydrogen impurities [155].

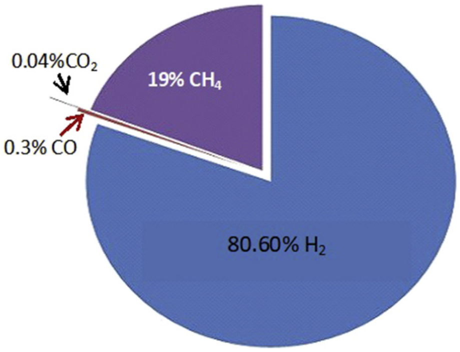

Fig. 16 – Flow of hydrogen on the out let of PSA [159].

Table 23 – Performance of PSA in different operating conditions.

Feed	Operating conditions	Performance	Recovery	Ref
CO:H_2:CO_2:N_2:Ar = 3: 88:2:6:1 mol%	Activated Carbon and Zeolite bed Temp: 34° C to 36C^0 Pressure: 35 bar (maximum)	99.97% pure H_2	Maximum 79%	[105]
CO:H_2:CO_2 mixture	Four adsorption beds of Activated Carbon, Temp: 21–40 °C	99.999% pure H_2	Purge/feed ratio: 0.001 Vent loss/feed ratio: 0.02	[153]
Biomass-derived syngas	Activated carbon Temp: ambient pressure	80.60% H_2	Over 95% H_2	[158]

ratio did not affect the purity and recovery. A study by Jinsheng Xiao et al. [154]; suggested that Zeolite is better adsorbent than activated carbon for CO adsorption. 99.99% pure hydrogen was obtained by 100 cycles with compact pressure swing adsorption of four layered bed of activated carbon at purge/feed ratio 0.001. A small-scale power plant based study done by Hamedani Rajabi Sara et al. [155]; found 46–50% hydrogen efficiency using PSA at pressure 7 bar [156] and ambient temperature, which is in line with the study [157].

Conclusion

The review indicate a sustainable and eco-friendly energy future. It also provide a total picture of biomass derived hydrogen production process and related techniques involved. Waste that is unexpected can be a source of energy (W2E). Waste management and energy production cost can be merged into one. Biomass gasification technology brought the changes and has been making a sustainable energy infrastructure that help to reduce the over pressure on fossil fuel. Everyday waste or biomass is a good source to support energy need. Bangladesh can utilized biomass (agricultural waste, forest residue and MSW) to meet the energy need for huge number of population. Biomass gasification is an economic way since many value added byproduct can be produced from the same source along with hydrogen that minimize the production plant expenditure. Gasification technology is getting popular and being placed into commercial use moreover, it can be portable. Current (2016) Production cost of hydrogen from different biomass is $2.1–3.0/gge whereas gasoline price is $ 2.26/gallon. Biomass derived hydrogen containing (40%) product gas subject to mainly four successive purity enhancement steps to get pure hydrogen. Many process parameters as discussed above need to be considered to lift up 40% hydrogen rich product gas to 99.99% hydrogen gas. A detailed optimization of process parameters for enhancement steps is under investigation that could be a breakthrough of the technology.

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