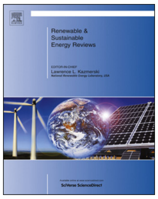
Renewable and Sustainable Energy Reviews 62 (2016) 1047–1062

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Progress in biomass gasification technique – With focus on Malaysian palm biomass for syngas production

Nor Afzanizam Samiran [a,*], Mohammad Nazri Mohd Jaafar [a], Jo-Han Ng [b,c,e], Su Shiung Lam [d], Cheng Tung Chong [a,e]

[a] *Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor Bahru, Malaysia*
[b] *Faculty of Engineering and the Environment, University of Southampton Malaysia Campus (USMC), 79200 Nusajaya, Johor, Malaysia*
[c] *Energy Technology Research Group, Engineering Sciences, University of Southampton, SO17 1BJ Hampshire, UK*
[d] *Eastern Corridor Renewable Energy Group (ECRE), Environmental Technology Programme, School of Ocean Engineering, Universiti Malaysia Terengganu, 21030 Kuala Terengganu, Terengganu, Malaysia*
[e] *UTM Centre for Low Carbon Transport in cooperation with Imperial College London, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia*

ARTICLE INFO

Article history:
Received 15 March 2015
Received in revised form
10 January 2016
Accepted 26 April 2016
Available online 18 May 2016

Keywords:
Malaysia
Syngas
Gasifier
Power generation
Palm biomass

ABSTRACT

Synthesis gas, also known as syngas, produced from biomass materials has been identified as a potential source of renewable energy. Syngas is mainly consists of CO and H_2, which can be used directly as fuel source for power generation and transport fuel, as well as feedstock for chemical production. Syngas is produced through biomass gasification process that converts solids to gas phase via thermochemical conversion reactions. This paper critically reviews the type of gasifiers that have been used for biomass gasification, including fixed bed, fluidized bed, entrained flow and transport reactor types. The advantages and limitations of these gasifiers are compared, followed by discussion on the key parameters that are critical for the optimum production of syngas. Depending on the biomass feedstock, the properties and characteristics of syngas produced can be varied. It is thus essential to thoroughly characterise the properties of biomass to understand the limitations in order to identify the suitable methods for gasification. This paper later focuses on a specific biomass – oil palm-based for syngas production in the context of Malaysia, where palm biomass is readily available in abundance. The properties and suitability for gasification of the major palm biomass, including empty fruit bunch, oil palm fronds and palm kernel shells are reviewed. Optimization of the gasification process can significantly improve the prospect of commercial syngas production.

Contents

---

[*] Corresponding author. Tel.: +60 7 5534755.
E-mail address: afzanizamsamiran@gmail.com (N.A. Samiran).

http://dx.doi.org/10.1016/j.rser.2016.04.049
1364-0321/

1. Introduction

The world's energy supply is dominated by the gradually depleting non-renewable fossil fuel. Production of oil, coal and gas is expected to decrease exponentially after reaching peak production in year 2015, 2052, 2035, respectively [1,2]. The huge consumption of fossil fuels is mainly driven by the ever increasing energy demand resulting from growth in global population and economical activities. Another major issue brought by fossil fuel burning is environmental pollution. The excessive emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are detrimental to the environmental and human health [3]. These issues drive the development of renewable energy technologies.

Synthesis gas (or syngas) is regarded as one of the promising alternative energy due to its environmentally clean fuel characteristic. Syngas is produced through gasification process from carbonaceous materials by thermal cracking reactions [4–6]. It consists mainly of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen (N_2), water vapor, methane (CH_4) and other hydrocarbons [5,7,8]. Syngas is well suited for various applications, including electricity generation and transport fuel production [9,10]. Primarily, syngas is used for power generation where it can be directly consumed as gaseous fuel to produce electricity and heat. Most of the harmful pollutants can be removed in the post-gasification process prior to combustion. In addition, syngas is widely used as key intermediary in the chemical industry to produce methanol, dimethyl ether, and methyl tert-butyl ether for liquid transportation fuel [11].

One of the key challenges of operating with syngas is the variation in chemical composition which can affect the combustion process [7]. Syngas composition varies depending on the feedstock and production methods. There are many types of feedstock that can be used to produce syngas such as biomass, coal, refinery residual, organic waste and municipal waste [12]. Biomass, being the fourth most abundant energy sources after coal, oil and natural gases, is regarded as a good candidate to produce renewable, sustainable and environmental-friendly energy source, which currently supplies 14% of the total global energy consumption [13,14]. In Malaysia, the agricultural sector contributes about 12% to the gross national income (GNI). A significant 8% of GNI comes from palm oil plantation with a gross value over $22.31 billion USD in 2014, making it the fourth largest source of national income [15,16]. Large quantity of biomass is produced from palm plantation, which could potentially be used as feedstock for syngas production. However, most of the palm biomass are either landfilled as waste or left on plantation ground for mulching as organic fertilizer [17]. There is a lack of initiative to process these biomass to become value added downstream products due to a lack of available efficient processing technology and poor management [17,18].

One potential use of palm biomass is as co-firing fuel in boiler system. However, most boiler system installations in Malaysia are still operating with low-pressure boilers with less than 40% overall cogeneration efficiency. Almost 77% of oil palm mills in Malaysia use combustion system with high CO_2 emissions [18]. Therefore, gasification system with combined heat and power (CHP) system is one potential technology that can replace conventional system to improve the biomass conversion efficiency, as well as to reduce carbon emission.

The objective of this paper is to critically review the state-of-the-art biomass gasification technologies, production methods, characteristics and governing parameters that affect the production of syngas. Understanding the biomass-to-syngas conversion processing route is important in order to assess the feasibility of gasifying palm biomass as alternative renewable energy source. This study also reviews the availability, current state, characteristic and potential of various palm biomass as solid feedstock to produce syngas via gasification method in the context of Malaysia.

2. Gasification of biomass to produce syngas

Gasification of biomass is a promising method to produce syngas. The raw product of the gasification process, usually called "product gas" or "producer gas" consists of stable chemical species. Producer gas contains CO, H_2, CH_4, aliphatic hydrocarbon, benzene, toluene and tars (besides CO_2 and H_2O) and is formed at low temperature (below 1000 °C) [19,20]. H_2 and CO typically contribute 50% of the energy in the product gas, while the remaining energy is contained in CH_4 and (aromatic) hydrocarbons. While the term "syngas" usually does not apply to the raw gas, it is widely used as an industrial shorthand to refer to the product gas from all types of gasification processes [21,22]. Fig. 1 shows the generic gasification process from which syngas is produced. Syngas is produced at high temperature (above 1200 °C) where feedstock is converted into H_2 and CO (besides CO_2 and H_2O) [19].

Generally, biomass conversion technology can be classified into three main categories, namely thermochemical, biological and physical conversion [20]. Gasification process is a thermochemical conversion technology where biomass feedstock is converted into higher heating value fuel [23,24]. The highlighted route in Fig. 2 indicates the production of syngas through gasification method. Gasification process can be utilized to produce syngas for combustion in boiler, turbine and internal combustion engines. Additionally, syngas is also produced for downstream application such as chemicals [21,25–27]. Before syngas can be used for downstream application, gas cleaning is necessary to eliminate unwanted by-product as shown in Fig. 1 [28,29]. Gasification reactors operation typically consist of four steps, namely drying, pyrolysis/devolatilization, reduction and combustion as detailed in Fig. 3 [21,22].

During gasification conversion process, unwanted by-products such as tars, impurities and ash will be produced. Tars consist of a complex mixture of hydrocarbon materials, which need to be removed or further processed to prevent it from condensing at

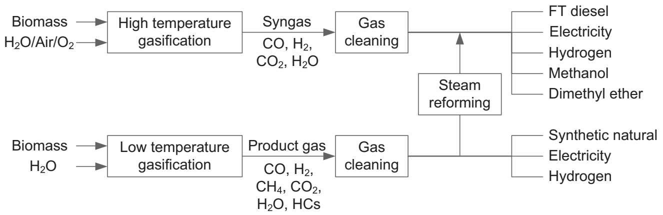


Fig. 1. Production of syngas and product gas and their typical application [19].

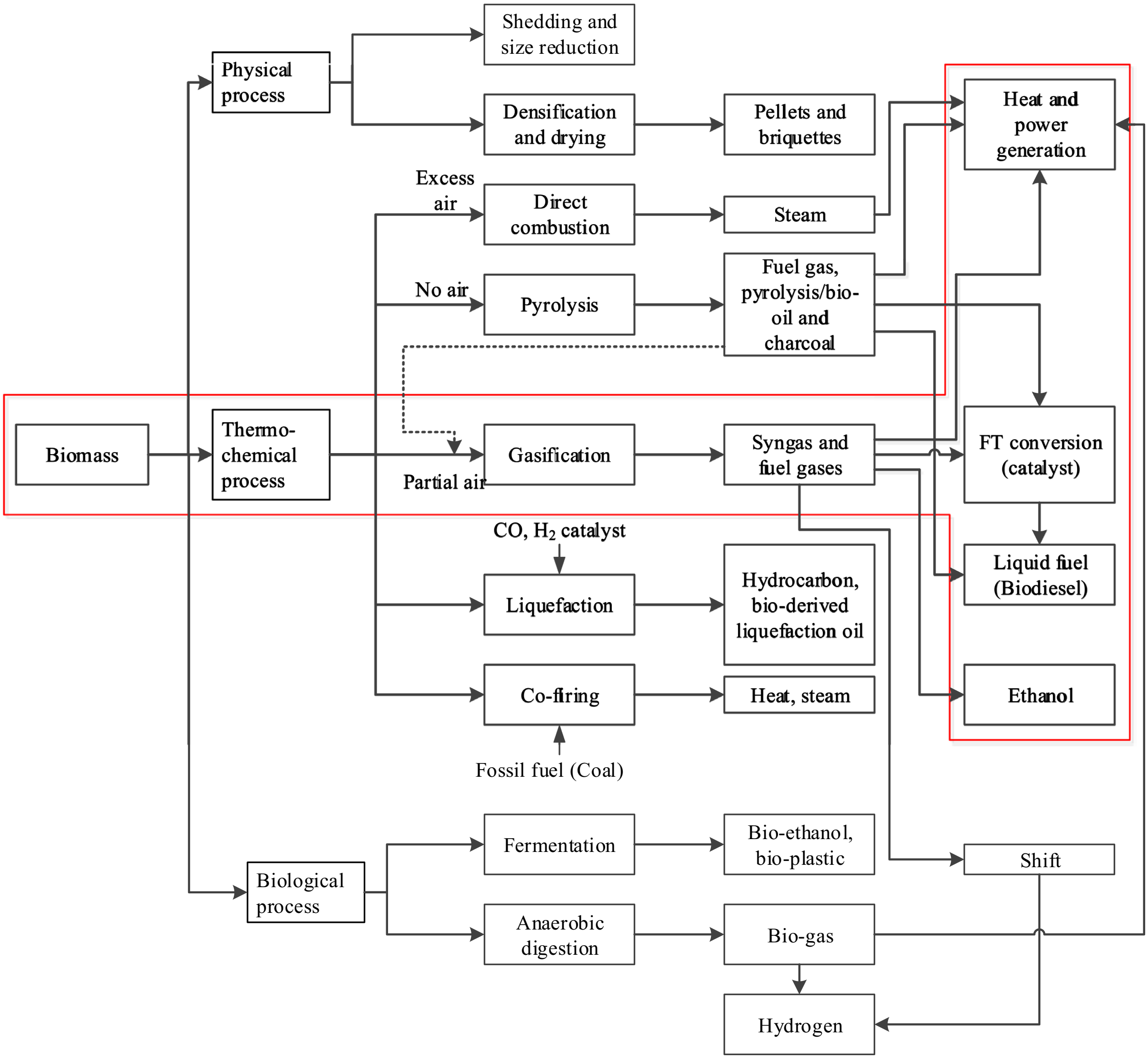
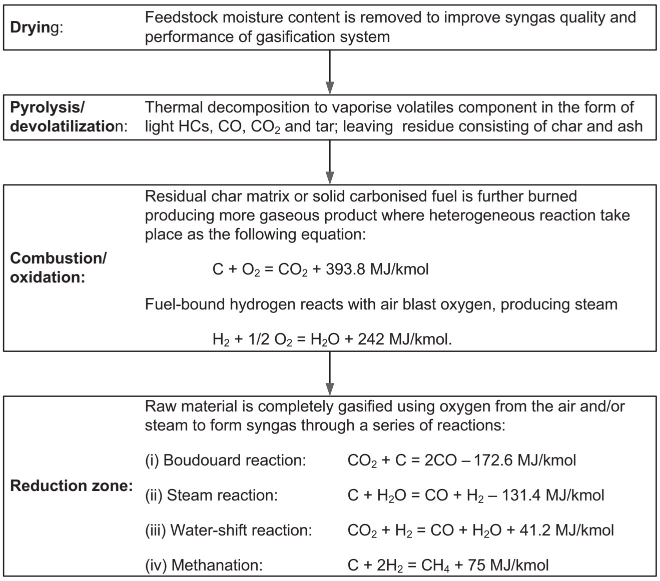


Fig. 2. Technological pathways for biomass conversion into alternative fuels. The highlighted route indicates production of syngas through gasification method. Figure adapted from [28,30,31].


Drying: Feedstock moisture content is removed to improve syngas quality and performance of gasification system

Pyrolysis/ devolatilization: Thermal decomposition to vaporise volatiles component in the form of light HCs, CO, CO_2 and tar; leaving residue consisting of char and ash

Combustion/ oxidation: Residual char matrix or solid carbonised fuel is further burned producing more gaseous product where heterogeneous reaction take place as the following equation:

$$C + O_2 = CO_2 + 393.8\ \text{MJ/kmol}$$

Fuel-bound hydrogen reacts with air blast oxygen, producing steam

$$H_2 + 1/2\ O_2 = H_2O + 242\ \text{MJ/kmol.}$$

Reduction zone: Raw material is completely gasified using oxygen from the air and/or steam to form syngas through a series of reactions:

(i) Boudouard reaction: $CO_2 + C = 2CO - 172.6$ MJ/kmol

(ii) Steam reaction: $C + H_2O = CO + H_2 - 131.4$ MJ/kmol

(iii) Water-shift reaction: $CO_2 + H_2 = CO + H_2O + 41.2$ MJ/kmol

(iv) Methanation: $C + 2H_2 = CH_4 + 75$ MJ/kmol

Fig. 3. General process of gasification (adapted from [20–22,24,27]).

downstream of the equipment [32,33]. Tar can also cause serious problems including fouling of engines and deactivation of catalysts due to its condensation and polymerization characteristics respectively [32]. Impurities that are present in the solid feedstock contain sulfur, nitrogen, chlorine that need to be removed from the producer gas and syngas [34]. Additionally, solid ash residue which is inorganic and non-combustible should be separated from the syngas products [14,35].

2.1. Type and selection of gasifier

Different reactor designs and gasification technologies have been established to accommodate various types of fuels. Since fuel types vary significantly in chemical, physical and morphological properties depending on feedstock, it is important to choose the appropriate gasifier. Biomass is known to be more difficult to gasify compared to fossil fuel due to the presence of complex lingo-cellulosic structures. However, experimental data and modeling of the gasification process in the reactor can be utilized to design biomass gasifier. The former practical approach models the size, optimizes operation of an existing gasifier and explores operational limits, while the latter simulates the thermochemical

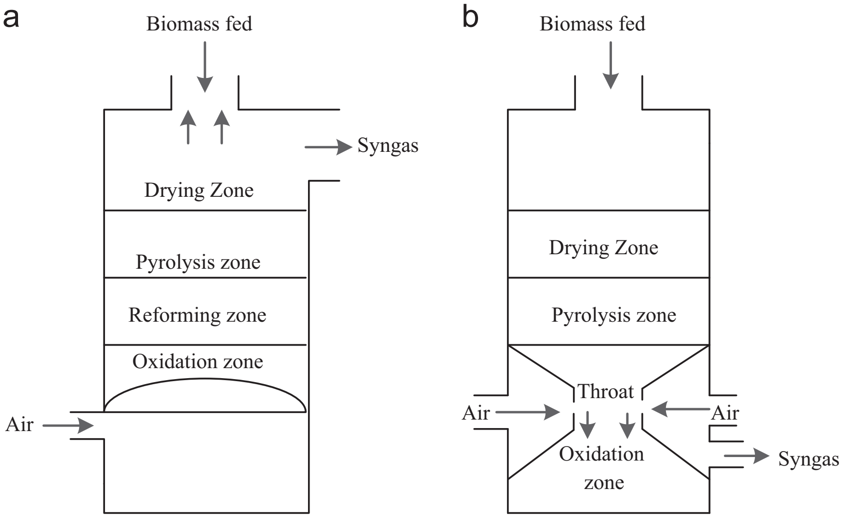


Fig. 4. Configuration and operating mechanism for (a) updraft and (b) downdraft gasifier.

process and mechanism inside the gasifier by taking into account the properties of biomass [36].

Four types of gasifiers: fixed bed, fluidize bed, entrained flow and transport reactor are promising technologies for gasification of biomass and thus will be critically reviewed in the following section. All four gasifying systems have relative benefits and drawbacks with respect to fuel type, application and operation, thus presenting potential technical and economic advantages under certain operating conditions. Performance of gasifier is dependent on the operational condition, stability, gas quality and pressure losses in the system. This section examines the selection of gasifier criteria based on the consideration of feedstock size distribution, bulk density and propensity for char formation under working conditions of different gasifiers [37].

2.1.1. *Fixed-bed gasifier*

Fixed-bed gasifier gasifies solid biomass using a cylindrical reactor. The process involves a bed of feedstock that is maintained at a constant depth, with the addition of fuel from the top of gasifier. It has a stationary reaction zone typically supported by grate [38]. Overall, there are two types of reactors used for fixed-bed gasifier, i.e. updraft and downdraft reactors, as illustrated in Fig. 4. [39]. The downside of this type of gasifier is the difficulty in maintaining appropriate mixture and temperature in the reaction area, hence the final composition of the syngas obtained can be inconsistent [29].

2.1.1.1. Updraft fixed bed gasifier. Updraft (counter-current) gasifier requires an opposite flow direction for the feedstock and gasifying agent such air, oxygen or steam [39,40]. Biomass is fed from the top of reactor, moves down through a drying zone (100 °C), followed by a pyrolysis zone (300 °C) where char and gaseous species are produced. At the gasification/reforming zone (900 °C), char moves down to the bottom of the gasifier to react and combust in the oxidation zone (1400 °C) with the incoming gasification agent [21,29,38]. Combustion of char is completed with the production of CO_2 and H_2O [29]. The up-flowing hot gas stream carries gaseous pyrolyzed products upwards to gasify the incoming feedstock in the upper region of the bed, where they are reduced to H_2 and CO and cooled to 400–750 °C [40,41]. The reducing gases (H_2 and CO) will continue to move up and pyrolyze the descending dry biomass before leaving the reactor at a low temperature [24].

The particle size range of feedstocks used for this type of gasifier is typically 2–50 mm. Operating pressure range in these gasifier is 0.15–2.45 MPa and the residence time is in the order of 15–30 min [22,33]. The long residence time of combustion to achieve complete gasification reaction results in low throughput and efficiency [42]. The operating conditions of various types of gasifiers are shown in Table 1.

Table 2 and Table 3 compares the advantages and disadvantages of different gasifiers. The main disadvantage of producer gas from updraft gasifier is the formation of high level of tars of about 10–20% by weight, which requires intensive post-cleaning [43,44]. Tar and some oxygenated compound are generated from low temperature gasification process. The produced tar in vapor form is condensed on the relatively cold descending fuel or is carried out of the reactor with the product gas [29]. Updraft gasifier has the advantage of producing syngas with low ash content due to the relatively high temperature achieved at the bottom of the reactor, which is close to the ash discharge point [43].

Since gas product from updraft gasifier has high content of tar, it is not recommended for engine applications but more suitable for thermal application [19,43]. The high content of CO_2 produced from biomass from updraft gasifier is another factor that impedes the production for liquid transportation fuels [39]. Gunarathne et al. [45] used a pilot scale updraft high temperature agent gasifier to produce syngas, in which the system operates with air/steam as gasifying agent and biomass pellet as feedstock. The syngas produced has relatively high low heating value (LHV) of 7.3–10.6 MJ/Nm^3.

2.1.1.2. Downdraft fixed bed gasifier. Downdraft (or co-current) gasifier is a reactor that operates with the primary gasification air introduced at or above the oxidation zone in the gasifier. The schematic of the downdraft gasifier is shown in Fig. 4b [21,40]. The feedstock and oxidants are fed simultaneously into the gasifier. Since producer gas is removed at the bottom of the reactor, feedstock and gas move in the same direction [39]. Solids and vapors generated from the pyrolysis zone react with the introduced air at the “throat” that supports the gasifying feedstock at atmospheric pressure [21]. The contraction area is where gasification reaction occurs. At the oxidation zone of the throat, the gasifying agent is distributed homogenously while the temperature is maintained at approximately 1000 °C. During the downward movement, acid and tarry distillation products from the fuel pass through a glowing bed of charcoal and converted into syngas [46]. The high temperature exhaust steam exits the reactor at about 700 °C [47].

Table 1
Comparison of various gasifier types.

Type of gasifier	Fixed-bed updraft	Fixed-bed downdraft	Bubbling bed	Circulating bed	Transport reactor	Entrained flow
References	[29,38–40,43,44,55,84,85]	[29,38–40,46,47,55,86–88]	[23,38–40,55,57,62, 89,90]	[29,38,55,56,65,66,73,83,85,90–92]	[29,38,40,71]	[29,38,55,73,80,83,93–95]
Combustion temp. (°C)	1300 (slurry feed) and 1500–1800 (dry feed)	800–900	800–1000	900–1200	900–1200	700–1500
Outlet temperature (°C)	425–650	700–800	800–1000	1000–1200	600–1050	1200–1500
Feedstock size (mm)	2–50	10–300	< 5	< 10	< 0.05	< 0.1
Preferred feedstock type Feedstock	Capable for biomass with high moisture	Low moisture biomass	Any biomass	Any biomass	Any biomass	Any biomass
Residence time (s)	900–1800	900–1800	10–100	10–50	1–10	1–5
Maximum fuel moisture (%)	60	20	< 55	< 55	< 20	< 15
O_2/feed (Nm^3/kg)	0.64	0.64	0.37	0.37	1.06	0.37
Gas LHV (MJ/Nm^3)	5–6	4–5	3–8	2–10	-NA-	4–10
Tar (g/Nm^3)	50–200	0.015–0.3	3–40	4–20	-NA-	< 0.1
Power output (MW)	< 20	< 10	10–100	10–100	> 100	> 100
Carbon conversion (%)	Closed to 100	93–96	70–100	80–90	97.5	90–100

Table 2
Advantages of various gasifier types.

Properties	Fixed-bed updraft	Fixed-bed downdraft	Bubbling bed	Circulating Bed	Transport reactor	Entrained flow
References	[40,96]	[29,53,97]	[55,98,99]	[56,92,100]	[40,71,75]	[38,74,81]
Heat/thermal system	Efficient use of thermal energy released by oxidizing solid carbon. Gases exiting the bed are cooled by the incoming fuel.	–	– Nearly uniform temperature distribution throughout the reactor – Provides high heat transfer rates between the inert material, fuel and gas	– High heat transport rates possible due to high heat capacity of bed material – Suitable for rapid reactions	High throughput and heating rate	–
Feedstock	Wide range (inclusive of high moisture and inorganic content such as municipal solid wastes)	Wide range	Wide range, various particles sizes	–	Wide range	Wide range
Syngas quality	–	Minerals remain with the char /ash, reducing the need for a cyclone	Yields uniform composition of syngas with low tar and unconverted carbon	Low tar and unconverted carbon	Reducing the tendency to crack the volatiles and form tars	Syngas does not contains tar and phenolic compound
Operating conditions	–	99.9% of tar formed is consumed, requiring minimal cleanup, suitable for engine applications	High conversion	High conversion rate	– Improved gas mixing solids – Better conversion rate – Better interphase transport – Simultaneous removal of sulfur	– Higher throughput and better product gas quality – In-situ sulfur removal
Commercial value	Proven technology, simple and low cost process;	Proven technology, simple and low cost process.	Proven technology, medium cost process;	Proven technology, medium cost process;	–	–

The feedstock requirement for downdraft gasifier is related to the size of the throat. Typically, the feedstock particle size range is around 1–30 cm. The physical limitation of the particle size leads to a practical upper limit to the capacity of this configuration of about 500 kg/h or 500 kWe (kilowatt-electric) [29]. The size of the throat forms a limitation for the scale-up process, and therefore the downdraft gasifier is not suitable for the implementation in a large-scale plant [48].

The downdraft gasifier is suitable to convert high volatile fuel derived from biomass for power generation [49]. The feedstock used should be relatively dry, limited to about 30% moisture and with low ash content ($<1\%$ in weight) [50,51]. High volatile matters have high tendency to vaporize and thus can be ignited easily. The highly reactive vaporized matters in the oxidation zone is useful for combustion application.

For the downdraft gasifier, the high temperature at the gasifier exit enables low tar production that is less than 0.5 g/m^3 [52]. The low tar content of this gasifier makes it advantageous for small-scale electricity generation by using an internal combustion engine [48]. The high local temperatures in the oxidation zone could cause melting of some ash constituents [39,53]. Galindo et al. [51] used a two-stage air supply in downdraft gasifier to improve the quality of syngas. The two-stage air supply system was developed based on the injection of the gasification fluid at both combustion and pyrolysis zone. The primary process in pyrolysis zone ensures partial oxidation of biomass to allow production of higher syngas concentrations with low tar content. The two-stage air supply reduced the tar content in the syngas by up to 87%. The effect on the tar reduction is a consequence of temperature increase in the pyrolysis and combustion zones. The temperature in pyrolysis zone was higher compared to single stage air supply that led to the increase of temperature in the combustion zone [51]. Comparison of the advantages of different gasifiers is shown in Table 2.

2.1.2. *Fluidized bed gasifier*

For fluidized bed gasifier, air is blown through a bed of solid particles at sufficient velocity to maintain the particles in a state of suspension [39]. The bed is externally heated to provide sufficient energy for the endothermic steam reforming reaction process during operation. Thus, feedstock is fed into the gasifier reactor to interact and mix with the bed of solids at elevated temperature [50]. The process is repeated rapidly with newly arrived particles for drying and pyrolysis circulation to produce char and gases [54]. The advantage of fluidized bed gasification over fixed bed gasifier is the uniform temperature distribution achieved in the gasification zone [50].

Fluidized bed gasifier typically operates at temperatures of 800–1000 °C to prevent ash from building up [54]. This type of gasifier has high thermal inertia with vigorous mixing during gasification process apart from permitting the control of ash content, making it suitable to operate with wide range of fuels, e.g. biomass fuels, municipal solid waste (MSW), lignite and low-rank coals [40,55]. The fluidized bed gasifier is widely used for large-scale biomass gasification plants [56–59].

2.1.2.1. Bubbling fluidized bed (BFB) gasifier. Bubbling fluidized bed gasifier is characterized by discrete bubbles of gas relatively low velocity (<5 m/s). It consists of a vessel with a grate at the bottom through which air is introduced as shown in Fig. 5a. Above the grate is a moving bed of finely grained biomass materials. Particles of biomass are driven into a bed of hot sand fluidized by recirculating product gas [32,59–61]. Jakkapong et al. [55] regulated the steam flow rate at 1.26 kg/h through the bed to achieve fluidization at low velocity of around 0.18 m/s. Bubbling fluidized bed gasifier is integrated with a fluidized bed, where a strong vortex (or rotation) of gas-solid flow is introduced to intensify the fluid motion in the reactor, providing a homogeneous temperature condition for biomass reaction [62]. Since the bed consists mostly of ash, temperature is maintained at 700–1000 °C by controlling the air/biomass ratio to avoid agglomeration. Alternative bed material (such as alumina) can be used to avoid the ash from softening and developing defluidization phenomena [32,56].

Biomass in bubbling fluidized bed is pyrolyzed in the high temperature bed to form char with gaseous compounds. The char and gases compounds are cracked by contacting with hot bed material. Cracking process can reduce tar and therefore, product gas will have low tar content, typically 3–40 g/Nm^3 [55]. The operating conditions for this gasifier are shown in Table 1. Additionally, the stirred-reactor mixing that found in this gasifier separates the extracted ash/char particles from flue gas by a cyclonic device. The process is followed by returning solids into the fluidized bed, forming an internal solid circulation [62]. Kratas et al. [58] used bubbling fluidized bed gasifier with air and steam as gasifying agents. The gasifier was operated with cotton stalk and hazelnut shell as feedstocks. The effects of equivalence ratio and steam to fuel ratio variation on the CO, CO_2, CH_4, H_2 and N_2 concentrations and the LHV of the product gas were investigated. Hazelnut shell was found to produce syngas with higher LHV than cotton stalk by using both gasifying agents since the calorific value of hazelnut shell (4493 kcal/kg) is higher than cotton stalk (3990 kcal/kg). Steam was reported to be the more effective gasification agent compared to air, as the LHV was increased by 44% and 84% for hazelnut shell and cotton stalk respectively. The increase of LHV corresponds to the increase of reactive component H_2. The participant of water (steam) in water gas shift reaction increases the production of H_2 [58].

2.1.2.2. Circulating fluidize bed (CFB) gasifier. Circulating fluidize bed (CFB) is a circulation process of bed material with volatiles

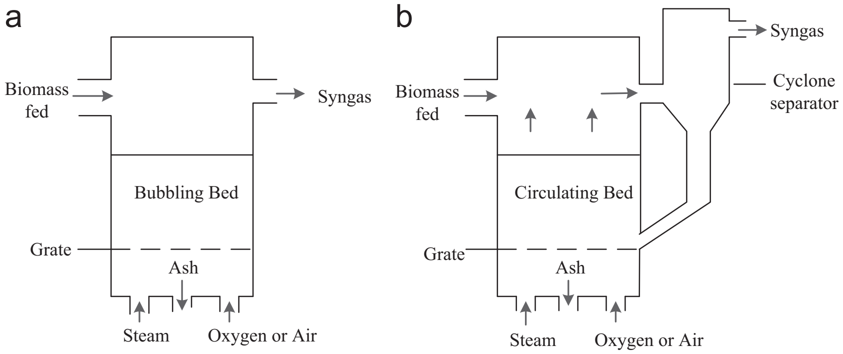


Fig. 5. Schematics of the (a) bubbling bed and (b) circulating bed gasifiers.

(including hydrogen gas and char) derived from raw feedstock. The circulation process takes place between the reaction vessel and a cyclone separator as shown in Fig. 5b. The bed material and char are returned to be combusted in the reaction vessel while ash is removed through cyclone separator. Bed particles enter the riser through orifices at the riser base to achieve solid mass fluxes up to 700 kg/m^{2}s at gas velocities between 5.5 and 8.5 m/s, at which the recirculated product gas, sand and biomass particles move together [56,57,60,61]. Biomass in CFB is rapidly pyrolyzed to produce hydrocarbon gases. Tar is quickly captured by the bed in the gasifier while coke on the bed is gasified with steam [57].

In a CFB reactor, the circulating solids are characterized by thorough mixing and high residence times within the solid circulation loop [63,64]. The absence of bubbles prevents gas from bypassing the bed [38,55]. The advantage of using rapid reaction at high heat transport rate in the reactor is the reduced tar in the syngas compared to the commonly-adopted bubbling bed [62,65]. Meng et al. [66] utilized a 100 kWth atmospheric pressure operated steam-oxygen blown CFB gasifier to investigate the effect of two types of sawdust pellet and willow wood biomass feedstock on syngas composition. The result shows that the average concentration of H_2 obtained was around 20–30% over the temperature range from 800–820 °C for both feedstocks. The range of H_2 composition obtained is relatively high for gasification of biomass [29,67,68].

2.1.2.3. Transport reactor gasifier. The operating mechanism for a transport reactor gasifier is midway between a fluidized bed and an entrained bed gasifier [40]. The schematic diagram of a transport reactor gasifier is shown in Fig. 6. Transport reactor gasifiers normally operates at higher gas velocity (~15 m/s) which require smaller diameter of gasifier vessels so that all bed materials can be transported up the reactor by gas flow [40,69]. In this gasifier, feedstock enters with gas (either air or oxygen/steam) into an upward flow to react and fluidize the bed of feedstock [38]. For combustion mode, secondary air is introduced at high level of mixing to ensure uniform temperature distribution in the gasifier, usually below the ash fusion temperature (1000–1500 °C) to avoid ash melting, clinker formation and loss of bed fluidity [69]. Fly ash is recirculated to the furnace chamber as new bed material when firing fuel with low ash content to avoid losses of circulating materials [70]. The recirculation movement of fly ash and make-up sand ensures the mass of solids is kept in the bed inventory [70].

In this gasifier, feedstock is first devolatilized/gasified in the fluidized bed mixer followed by char combustion in a fluidized bed combustor (riser). This process increases carbon conversion and leads to high cold gas efficiency, contrary to other single-stage type gasifier which leads to lower cold gas efficiency at low operating temperature [71]. The temperature distribution in the transport reactor needs to be controlled critically to ensure the sulfur content produced during gasification process is low. High production of sulfur in the gasifier reactor is possible particularly during the direct desulfurization process [38].

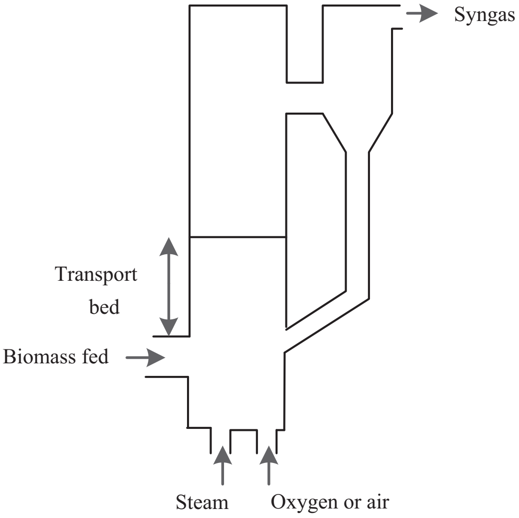


Fig. 6. Transport reactor gasifier, adapted from [72].

2.1.3. *Entrained bed gasifier*

Unlike moving bed or fluidized bed gasifiers, entrained flow gasifiers operate at high temperature of 700–1500 °C for biomass [42,73,74]. The composition of the product gas is very close to syngas quality [75]. The solid feedstock needs to be grinded into small particle size (<100 μm) for the feed system in order to achieve high conversion rate [40,76]. In the single-stage system as shown in Fig. 7a, feedstock and oxidant agents are fed concurrently into the burner at high velocity to gasify the biomass [75]. Flow velocity is high enough to establish a pneumatic transport regime. Biomass is completely oxidized with typical residence time around 1–5 s [74]. The two-stage entrained bed gasifier is shown in Fig. 7b. The gasifier uses super-heated crude gas in the first gasification zone before reacting with steam biomass injected in the second stage of gasification zone. This process is important to increase the syngas quantity and cool the slag [38,77–79]. Endothermic gasification reactions in the second stage serve to lower the exit temperature compared to a single stage design. This means lesser oxygen demand per mass of feedstock, and higher efficiency conversion rate to syngas [40].

Entrained bed gasifier requires pulverized feedstock with particle size of less than 0.1 mm [72,74,76]. This type of gasifier usually operates at high pressures of 2.94–3.43 MPa [40]. The temperature of gasification is up to 1500 °C with the residence time in the order of 1 s. The gasifier produces high yield of syngas and is suitable for less active feedstock due to its high temperature environment [72,75,80]. The high temperature environment effectively eliminates all hydrocarbons, oils and phenol formed during devolatilization stage, while the mineral matters in the feedstock are removed as slag [81]. Senapati et al. [82] studied the usage of entrained flow gasifier for powdery biomass feedstock such as rice husk, coconut coir dust and saw dust. The study showed the gasifier could reach high temperatures in the range of 976–1100 °C. The LHV of the syngas produced was relatively high at 7.86 MJ/Nm^3 with peak cold gas efficiency of 87.6%. Higher rate of oxygen supply can be used to achieve higher operating temperature in the gasifier to reduce cold gas efficiency [39]. The entrained bed gasifier has been used to produce syngas for synthesis of chemicals (ammonia, methanol, acetic acid), liquid fuels and also for power generation [38,76,83].

3. Energy mix in Malaysia

Overall, the use of biomass for energy production in Malaysia is not yet extensive. In 2013, less than 1% of the total energy in Malaysia was generated from biomass, compared to the 6% energy produced in Europe [102,103]. Table 4 shows the breakdown of electricity generation in Malaysia over the last three decades. The interest in using biomass for energy production is low despite the launch of Small Renewable Energy Power program (SREP) in May 2001 that promotes the use of agricultural waste for power generation [104–106]. After almost a decade since the SREP program was launched, only 65 MW of biomass power generation out of the targeted 350 MW was achieved [107]. From the overall renewable energy perspective, oil palm biomass contributes the most with 40 MW of grid-connected capacity, more than other renewable

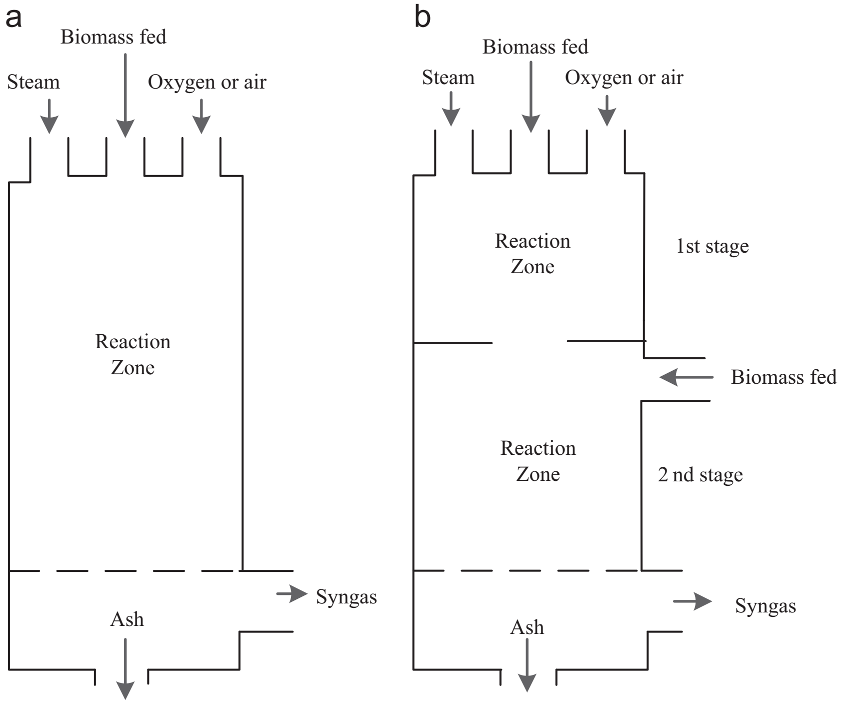


Fig. 7. Schematic of the (a) single stage entrained flow and (b) two stage entrained flow, adapted from [40].

technologies such as from biogas, small hydro, solid wastes and solar sources amounting to 4.95 MW, 12.5 MW, 5 MW, and 2.5 MW, respectively [108].

In 2009, the 'National Renewable Energy policy and action plan' was launched by the Malaysian government to enhance the utilization of renewable energy resources. This policy and action plan led to the enactment of the Renewable Energy (RE) Act 2011 with feed-in tariffs to provide a more attractive implementation of grid connected power generation from renewable energy resources. The New Renewable Energy Act 2011 revised the renewable energy target to 985 MW, 2080 MW and 21,000 MW by the years 2015, 2020 and 2050 respectively [112,113]. Syngas production from biomass for power and heat generation presents one feasible way to contribute to achieving the target set. The syngas produced can be used directly either in a standalone combined heat and power plant (CHP) or by co-firing in a large scale power plant [114,115].

Syngas is also expected to play a vital role with the increased activities of biofuel in Malaysia since it is also a key intermediary product to produce biofuel. Syngas produced from gasification followed by Fischer–Tropsch (FT) process is one of the promising routes to produce liquid biofuel for transportation [116,117]. The FT synthesis reaction is a process that converts syngas to a wide range of long chain hydrocarbon products like liquefied petroleum gas (LPG), hydrocarbon-based fuel (such as gasoline, diesel and jet fuel) naphtha, olefins, wax and oxygenated compounds (such as alcohols) [118,119]. The long chain hydrocarbon can be distilled, hydrocracked or upgraded to become liquid transportation fuels [118].

4. Malaysian palm biomass for syngas production

It is estimated that 80 million dry tonnes of solid biomass from palm is produced annually, contributing to 85.5% of the total biomass share in Malaysia [18,100,120]. Palm oil residues are generally produced as by-product from milling sector and plantation activities. The palm kernel shells (PKS), mesocarp fibers (MF), and empty fruit bunches (EFB) are the main residues generated through milling process during production of crude palm oil [121]. Other major residues such as oil palm fronds (OPF) and oil palm trunks (OPT) are obtained from cut-down in plantation site. During harvesting and pruning, OPF are also obtained [122]. Malaysia as a leading producer of palm oil has over 362 palm oil mills in operation that process 71.3 million tons of fresh fruit bunch annually. As a result, over 20 million tons of crop waste consisted of empty fruit bunch, fiber and shell were produced [123]. Table 5 shows the weight proportion and quantity per hectare for different types of oil palm biomass in Malaysia.

At present, biomass is typically confined to low value downstream activities such as biofuel conversion or used as direct fuel for power generation [28,123,126]. In Malaysia, about three quarters of the total solid biomass are used as fertilizer in plantation sites, where OPFs, trunks and EFBs are left in the plantation for biodegradation [127,128]. Some milling plant utilizes MFs, PKSs and EFBs from milling waste for steam power generation [127]. Table 6 shows the availability of palm biomass and the potential energy generation based on the availability of specific palm biomass. The availability of PKS and MF is relatively low compared to EFB, frond and trunk. PKS and MF are mostly used as solid fuel feedstock for steam generation to produce electricity [129]. Part of the biomass were used for wood industry, animal feed and other niche downstream applications, such as wood products, bioenergy and pellets [130–132].

Prior to converting biomass into different phase of fuels, thorough characterization of the chemical and phase compositions properties is needed [134]. Previous research utilized structural composition, ultimate and proximate analysis for characterization of solids fuel to determine the properties and quality of biomass [63,134]. Structural composition analysis is performed to examine the lignocellulose content in biomass, i.e. cellulose, hemicellulose and lignin. These information are important for the development of fuels and chemicals, study of combustion phenomena and estimation of HHV [135,136]. Ultimate analysis is conducted to determine the elemental content in percentage by mass. Information such as the exact amount of N, S and Cl in biomass content

Table 3
Disadvantages of various gasifier types.

Properties	Fixed-bed updraft	Fixed-bed downdraft	Bubbling bed	Circulating bed	Transport reactor reactor	Entrained flow
References	[29,38–40,93]	[29,48,99]	[54]	[29,38,39,72]	[38,72]	[40,59,101]
Heat/ thermal system	Volume of steam requirement is high	Lower efficiency resulting from the lack of internal heat exchange as well as the lower heating value of the gas	–	– Temperature gradients occur in direction of the solid flow Heat transfer less efficient than bubbling fluidized bed	–	Energy needs to be recovered due to the high temperature operation for efficient use of fuel
Feedstock	–	– Requires feed drying to a low moisture content (< 20%) – Inability to operate on a number of unprocessed fuels	–	– Specific range of feedstock particle size	–	Costly feed preparation is needed for woody biomass process
Syngas quality	Syngas contains high tar and phenolic compound	Higher ash content syngas (slagging) to a larger extent than updraft gasifiers	–	–	–	–
Operating conditions	High loss of fine particles from feed preparation	The fuel gas produced leaves the gasifier at high temperatures, requiring cooling before use.	Large bubble size may result in gas bypassing the bed	High velocity due to particle size results in equipment erosion	–	–
Commercial value	-	–	–	–	Not well proven	Use of expensive construction materials and high temperature heat exchangers to cool syngas

Table 4
Malaysia energy mix (%) in electricity generation [109–111].

Source	1980	1990	2000	2005	2010	2012	2013
Oil/diesel	87.9	71.4	4.2	2.2	0.2	5	2.3
Natural gas	7.5	15.7	77.0	70.2	55.9	46	50.4
Hydro	4.1	5.3	10.0	5.5	5.6	7	8.4
Coal	0.5	7.6	8.8	21.8	36.5	41	38
Biomass	–	–	–	0.3	1.8	1	0.9

is useful for environmental impact study, whereas information such as C, H and O can be used for estimating heating value [134,136]. Proximate analysis assesses the mass percentage of moisture, volatile matter, fixed carbon and ash contents. In the context of biomass, high amount of ash produced is undesirable and can cause ignition and combustion problems [134]. High volatility matters present the advantage of requiring lower temperature for decomposition and reaction process [38]. The heating value of biomass is proportional to the content of carbon and volatile matter [136]. The characteristics and properties of oil palm biomass are reviewed in the following section.

4.1. *Empty fruit bunch (EFB)*

Empty fruit bunch is one of the main solid by-product generated from palm oil mill processing [137]. There are small mill plantations in Malaysia with integrated facilities that utilize shredded EFB for power production purpose [106,132]. However, due to the high upfront investment cost needed for the preprocessing of biomass such as shredding and pressing of biomass, most plant owners have been reluctant to use EFB for power generation. Instead, most EFBs are simply burned in incinerators to produce fertilizer [128]. The incineration process produces excessive emissions that are detrimental to the environment [138].

Understanding the characteristics of EFB allows better handling and utilization of resources more efficiently, especially in the application for power generation. Biomass fundamental properties such as moisture content, particle size, density, element contents (e.g. C, H, N, S and O), structural constituent contents, ash content and volatile matter contents influence the suitability of EFB as fuel [139]. Studies have been conducted to characterize EFB as feedstock for energy production. The proximate analysis of EFB is shown in Table 7. EFB has relatively high content of moisture, indicating the need of excessive heat for drying. The high volatility and reactivity of EFB is a merit for the production of liquid fuel or other downstream activities. Syngas production is made feasible by the sufficiently high level of HHV of EFB (32.1 MJ/kg) [140].

4.2. *Palm kernel shell (PKS) and mesocarp fiber (MF)*

Palm kernel shells (PKS) and mesocarp fiber (MF) are by-products produced from palm oil mill processing [141]. The high content of carbon element in PKS and MF shows its potential to be used as solid fuel feedstock for steam generation to produce electricity [142]. Based on the proximate and ultimate analysis of PKS feedstock shown in Table 8, PKS contains the most significant amount of volatile matter despite a moderate amount of fixed carbon. The fuel moisture and ash content is low but the heating value is relatively high, making it a good source as feedstock compared to other palm biomass for power generation in the industry [126,143].

4.3. *Oil palm frond (OPF)*

Oil palm frond mainly consists of 40–50% cellulose, 20–30% hemicellulose and 20–30% lignin as shown in Table 9 [126,144].

Table 5
The weight proportion and quantity per hectare for the different types of oil palm biomass in Malaysia [124,125].

Source of residue	Type of residue	Description	Weight of the total source (%)	Quantity (million tonnes)[a]
Fresh fruit bunch (from palm oil mill)	Palm kernel Shell	Remains after palm kernel oil extraction	5	4.2
	Empty fruit bunch	Remains after removal of palm fruits	23.0	19.3
	Mesocarp fiber	Remains after crude palm oil extraction from fruit bunch.	13	10.9
Oil palm tree	Oil palm Frond	Replanting and annual pruning	20	24.8

[a] Based on 83.9 million tonnes of fresh fruit bunch processed in 2010.

Table 6
Availability and energy generated from palm oil biomass in Malaysia [113,154]

Biomass component	Quantity available (million tonnes)	Potential energy generation (metric tons)	Electric generated (GWh)
Reference	[133]	[133]	[106]
Empty fruit bunches	17.0	7.7	46,346.2
Palm kernel shell	5.9	2.8	5792.1
Fiber	9.6	4.4	1578.2
Palm kernel seed	2.1	0.95	–
Fronds and trunks	21.1	–	–

Table 7
Properties for empty fruit bunch [140].

Proximate analysis (wt% dry basis)		Ultimate analysis (wt% dry basis and ash free basis)		Lignocellulosic content (wt% dry basis)		HHV (MJ/kg)	
Moisture content		C	45.00	Cellulose	23.7	Pith	14.0
Pith	82.60	H	6.40	Hemicellulose	21.6	Branch	18.1
Branch	57.50	O	47.30	Lignin	29.2		
Volatile matter	71.20	N	0.25				
Fixed carbon	18.30	S	1.06				
Ash	7.54						

Table 8
Properties for Palm kernel shell (PKS).

Proximate analysis (wt% dry basis)		Ultimate analysis (wt% dry basis)		Lignocellulosic content (wt% dry basis)		HHV (MJ/kg)
Reference		[126,143]				[129]
Moisture content	5–11	C	45–50	Holocellulose-cellulose	25–40	
Volatile matter	65–75	H	5–7	Alpha-cellulose-hemicellulose	15–20	16.14
Fixed carbon	15–20	O	30–45	Lignin	35–45	
Ash	2–5	N	0.05–2.00			
		S	0.05–0.20			

Table 9
Properties for oil palm frond (OPF).

Proximate analysis (wt% dry basis)		Ultimate analysis (wt% dry basis)		Lignocellulosic content (wt% dry basis)		HHV (MJ/kg)
Reference	[122,145]		[122,126]		[126,144]	[129]
Moisture content	10–20	C	40–45	Cellulose	40–50	
Volatile matter	80–85	H	4–6	Hemicellulose	20–30	15–20
Fixed carbon	5–15	O	45–55	Lignin	20–30	
Ash	0.2–2.0	N	0.3–0.8			
		S	0.01–0.1			

Table 10
Comparison of syngas composition and heating value for gasification of palm biomass with other feedstock biomass

Biomass type	Dry gas composition (% vol.)				LHV (MJ/Nm^3)	Ref.
	CO	CO_2	H_2	CH_4		
OPF	25.3	8.2	9.6	1.2	4.8	[68]
EFB	16.6	19.24	5.6	4.3	5.9	[87]
PKS	10.4	0.0	82.1	11.4	13.8	[150,151]
	14.3	11.5	62.5	11.6	12.7	[151]
Coconut shells	21.3	11.8	13.5	1.5	4.9	[68]
Hazelnuts shells	19.6	10	12.7	2.0	4.7	[68]
Furniture wood	24.0	14.7	14.7	2.0	5.5	[68]
Woody biomass	20.3	8.3	17.8	1.7	5.3	[68]

Previous studies showed that OPF has high potential to be used for gasification [145]. According to Fiseha et al. [122], the volatile matter content of OPF is 83.5%, comparable to beach wood and sugarcane bagasse, which are 82.5% and 85.61%, respectively. Other feedstock such as rice husk and coconut husk biomass contain 68.25% and 70.3% of volatile matter, which is lower than OPF [82,122,146,147]. The high volatile matter content in OPF implies high reactivity and is suitable for thermochemical energy conversion process such as pyrolysis and gasification for syngas production [68]. OPF has the highest cellulose and lowest lignin and ash contents compared to other oil palm biomass such as EFB, shells and trunks [122]. Lignin is the most difficult component to be thermally decomposed and accounts for most of the unconverted matter in ash and char [148,149]. Therefore, the high cellulose, low lignin and ash compositions of OPF is advantageous as gasification fuel [148].

5. Characteristics of palm biomass-derived syngas

The characteristics of syngas derived from palm biomass were studied by some groups [68,87,150]. Table 10 shows the comparison of syngas composition and heating value for gasification of palm biomass with other biomass. Compared to other palm-related biomass, OPF produces the highest reactive component of CO content of 25.3% by volume but lowest in CO_2 using a downdraft gasification process [68]. The composition of H_2 and

CH_4 were low because of the depletion of moisture and pyrolysis gas in the feedstock as gasification time increased. When the moisture content was reduced in the feedstock, steam and hydrogasification reactions become slower. Therefore, formation of CO_2 by oxidation in the oxidation zone formed more CO when it passes through the char bed accumulated on the grate [122].

Gasifying EFB is another possible way for small scale power generation [152]. The high moisture content in EFB (60%) is a drawback for downstream applications that requires extensive drying to reduce the moisture level to $< 10\%$ [152]. Supercritical water gasification (SCWG) is an emerging technique that is suitable for the conversion of high moisture content biomass into hydrogen-rich syngas [153]. SCWG requires specific characteristics of water under supercritical conditions, such as low dielectric constant, thermal conductivity, ion product, viscosity and density to achieve effective biomass conversion reaction. H_2 and CO_2 were found to be the most dominant gases produced by SCWG method. Since EFBs are lignocellulosic compounds that are composed of hemicellulose, cellulose and lignin, higher amount of H_2 was obtained from hemicellulose. Hydrolysis of hemicellulose leads to formation of formic acid where it was reported to be prone to decomposition into CO_2 and H_2. Higher H_2 production shows the participation of water in water gas shift reaction. Cellulose and lignin produced the most CO and CH_4 respectively [153].

Table 10 shows the syngas derived from EFB contains high concentration of CO and CO_2 caused by thermal decomposition. Several factors have been known to increase the composition of H_2 in syngas derived from EFB. By increasing the bed temperature, endothermic methane steam reforming and dry reforming reactions occurs favoring the production of hydrogen. Tar reforming and cracking reactions are also prone to increase H_2 based on the following reactions:

$$\mathrm{C}_n\mathrm{H}_m(\mathrm{tar})+n\mathrm{H_2O}\leftrightarrow n+m/2\mathrm{H}_2+n\mathrm{CO} \quad \Delta H>0 \tag{1}$$

$$\mathrm{C}_n\mathrm{H}_m(\mathrm{tar})+n\mathrm{CO}_2\leftrightarrow (m/2)\mathrm{H}_2+2n\mathrm{CO} \quad \Delta H>0 \tag{2}$$

$$C_nH_m(\mathrm{tar})\leftrightarrow (m/2)\mathrm{H}_2+nC \quad \Delta H>0 \tag{3}$$

CO_2 is produced through water–gas shift reaction at low temperature. At high temperature, CO_2 is consumed through methane dry reforming, tar cracking and Boudouard reaction to yield more H_2 and CO, leading to a sharp decrease in CO_2 level. CH_4 production can also occur at high temperatures due to the cracking of tar to CH_4, CO and H_2. The generated CH_4 is consumed through steam reforming reactions and methane dry reforming [87].

CO_2 can also be affected by the presence of catalyst in gasification process. Besides capturing CO_2 or being a sorbent, catalyst assists in improving hydrogen production from gasification of EFB. The catalytic activity of cracking volatile compounds (tar) into light hydrocarbons and the reforming reactions significantly increase the concentration of H_2 [154].

Palm kernel shell is a well-known fuel for solid combustion due to its high calorific value. It is also a preferred feedstock for H_2 production via gasification process due to it high proportion of fixed carbon and volatile matter, low ash and moisture content [150,151]. PKS has shown wide application in industry to produce bio-oil, catalyst and bio-coal [155–157], but the potential for syngas production has not been capitalized. Previous study showed that gasification of PKS produce high H_2 content of syngas. Zakir et al. [151] used an integrated catalytic adsorption steam gasification system with fluidize bed to produce high hydrogen content syngas from PKS, of which over 80% of hydrogen was achieved [151]. Reza et al. [150] also achieved high hydrogen composition from PKS blended with polyethylene waste by utilizing catalytic steam gasification, indicating the suitability of PKS as feedstock for syngas production

The LHV of syngas is affected by factors such as feedstock, gasification method and temperature. Samson et al. [68] reported that LHV of syngas produced from OPF remained constant at 5.2 MJ/Nm^3 after the reactor temperature reaches 1100 °C using downdraft gasification process. The value obtained is higher than coconut shells and hazelnut shells as shown in Table 10. Pooya et al. [87] used EFB as feedstock in a fluidized bed gasifier and observed a maximum heating value of 5.88 MJ/Nm^3 for the syngas produced. HHV value obtained from the chopped OPF (17.3 MJ/kg) using unheated air was comparable to pelletized empty fruit bunch (EFB) but lower compared to woodchips (20.5 MJ/kg), pelletized bagasse (19.26 MJ/kg), pelletized wood (20.27 MJ/kg) and eucalyptus wood residues (18.14 MJ/kg).

6. Gasification process and parameter optimization

In general, the syngas yield and composition of gases produced from gasification are dependent on parameters including reaction temperature, gasifying agent, type of biomass, particle size, heating rate, operating pressure, equivalence ratio, catalyst addition and reactor configuration [28]. Studies on the development of gasification have been performed by many researchers to improve the efficiency and operability of gasifier, as well as the yield of syngas.

Gasification process is sustained by heat generated from a controlled amount of oxidant to conserve the reaction of gasification. Gasification agent or oxidant (air or oxygen) is added to solid fuel to produce gasified fuel. Some of the gasification reactions involve the precipitation of water or steam [147,158–160]. The use of catalysts such as dolomite, olivine and nickel-based inside the gasifier was shown to improve gas product quality, tar reduction and increase yield [35,161]. Other parameters such as steam to biomass (S/B) ratio, temperature, equivalence ratio, and biomass feed rate can be controlled to increase syngas yield and reduce formation of tar [162]. Table 11 elucidates studies of palm and other biomass gasification with various parameters that affect syngas production.

Nimit et al. [159] utilized oil palm frond as a feedstock for gasification process and showed that hydrogen mole fraction increases with decreasing reactor temperature. Samson et al. [68] used OPF as feedstock and reported that the concentration of H_2 in syngas increases in oxidation zone temperature for the range between 500 and 850 °C. At higher temperature, H_2 concentration drops slightly for temperature above 900 °C. Fiseha et al. [122] reported that preheating the gasifying air in oil palm fronds increased the volumetric percentage of H_2 from 8.47% to 10.53% and CO from 22.87% to 24.94%. Sivasangar et al. [153] utilized supercritical water gasification (SCWG) technique to gasify EFB. The study showed that hydrogen concentration increased with reaction time as the concentration of EFB increased from 0.05 g to 0.3 g. Mohammed et al. [163] investigated air gasification of EFB using fluidized bed gasifier. The study reported that increasing the operating temperature was enhanced the total gas yield where H_2 obtained 38.02% vol. and CO, 36.36 vol%. respectively. Fine particle size of feedstock also increases the composition of H_2. Finally, the equivalence ratio of 0.25 was found as the optimum value to attain a higher H_2 yield at volume percentage of 27.3%.

Pooya *et. al* [87] used a bubbling bed gasifier to produce syngas from EFB and reported that equivalence ratio of 0.21 was optimum to achieve maximum volumetric composition of CO, H_2, CH_4 and CO_2 at 16.6%, 5.5%, 4.3% and 19.2%, respectively. Ogi et al. [73] used EFB in entrained flow gasifier with H_2O (steam) and $H_2O + O_2$ as gasifying agent. The study found that conversion rate of gasification with steam was above 95% and hydrogen-rich syngas was obtained with H_2 /CO fraction of 1.8–3.9. Conversion rate increased

Table 11
Effect of different parameter to syngas yield and tar reduction for various type of biomass.

Biomass type	catalyst	Reactor type	Gasifying agent	Reaction temperature (°C)	Syngas yield	Tar reduction	Ref.
Oil palm frond	No catalyst	Semi-batch reactor	Steam	700	Energy ratio was increased by 33% with an increase in reactor temperature from 600 to 1000 °C.	-na-	[159]
Oil palm frond	No catalyst	Downdraft fixed-bed	Air	850	CO composition increase from 5% to 28% with increasing temperature from 500 °C to 1200 °C	–na–	[68]
Oil palm frond	No catalyst	Downdraft fixed-bed	Preheated air	985	Preheating air improved the composition for all component (H_2, CO and CH_4)	-na-	[122]
Empty fruit bunch	No catalyst	Entrained flow	Steam	900	Obtaining hydrogen rich gas with steam agent (H_2O)	Tar yield was very low ($<$ 1.0 wt%)	[73]
Empty fruit bunch	No catalyst	Bubbling fluidized bed	Air	600–1050	H_2 content increase from 7.3% to 12.4% with increasing temperature	-na-	[87]
Empty fruit bunch	No catalyst, calcined dolomite and tri-metalic (nano-NiLaFe/γ-Al_2O_3)	Fluidized bed	Steam and Air	800–900	Highest hydrogen produced by steam gasification with tri-metalic catalyst as 58 (%v/v)	-na-	[165]
Empty fruit bunch	-na-	Super critical water gasification (SCWG)	Deionized water	380	Hydrogen concentration increased as the EFB/water ratio increase to 0.3 g from 0.05 g (3.75 wt%)	-na-	[153]
Empty fruit bunch	-na-	Fluidized bed	Air	700–000	As temperature increased from 700 to 1000 ºC, the H_2 content increased from 10.27 to 38.02 vol%, CH_4 increased from 5.84 to 14.72 vol%, CO increased from 21.87% to 36.36%	-na-	[163]
Empty fruit bunch	-na-	Bubbling bed	Air	650–1050	Obtained maximum heating values (HHV) of 5.37 (MJ/Nm3), dry gas yield of 2.04 (Nm3/kg), carbon conversion of 93% and cold gas efficiency of 72%	-na	[87]
Empty fruit bunch	-na-	Entrained flow	Steam, steam + Oxygen	600–900	Conversion rate of gasification with steam was above 95% and hydrogen rich syngas was obtained with H_2/CO fraction of 1.8 to –3.9. As O_2 added to the steam, amount of CO_2 was increased, hence reduced the amount of H_2 and CO as well as calorific value.	–na-	[73]
Empty fruit bunch	CaO and MgO	Temperature program gasifier	Oxygen	50–700	Nano MgO enhances the production of H_2 released, high amount of CO_2. Nano CaO showed high production of H_2 and released significant low amount of CO_2	-na-	[164]
Palm kernel shell	No catalyst	Fluidized bed	Steam	600–750	H2 composition of 82.11 vol% is achieved at 675 oC	-na-	[151]
Pine Sawdust	Nickel based, dolomite, olivine	Two-stage catalytic and gasification	Steam	850	Yield increase up to 2.78 Nm^3/kg with increasing temperature at ≤ 850 °C	-na-	[161]
Wood chip and red pine	Ni-loaded brown coal char (Ni/BCC)	Fluidized bed and fixed bed	Steam	650	Gas yield increase up to 90 mmol/g by reducing the ratio of feedstock per catalyst.	-na-	[166]
Pine sawdust	Limonite iron ore and olivine	Fluidized bed	Steam	700–860	CO=17 mol/kg by olivine, H_2=5.0 mol/kg by iron ore at equivalent ratio 0.3	Tar reduces from 70 g/kg of biomass at ER 0.2 to 20 g/kg of biomass at ER 0.3. Limonite iron ore is more active in tar reduction than olivine which yield 15–25 g/kg of biomass	[167]
Pine sawdust	calcined natural olivine	External circulating countercurrent moving bed (ECCMB)	Steam	800	Increase from 0.6 Nm^3/g to 0.8 Nm^3/g with increasing S/B ratio	Decrease from 4 g/m3 and 25% to 2 g/m3 and 10%, respectively with increasing S/B ratio	[162]
Pine sawdust	dolomite	Fixed bed	Steam	600–900	1.15–2.53 Nm^3/kg with increasing temperature	Tar reduced 4.7–0% with increasing S/B ratio	[168]
		Fixed bed	Steam	500		-na-	[169]

Eucalyptus sawdust	Calcined dolomite and Nickel oxide				Formation of H_2 and co increase from 47.7 to 71.5 mol/kg and from 11.5 to 15.6 mol/kg with the increasing amount of dolomite		
crude glycerol (CG)+olive kernel	No catalyst	Co-current (downdraft)	Steam	750–850	Increased from 0.4 to 1.2 Nm^3/kg for the mixture of 49 wt% of CG in biomass	Tar yield decreased from 19.5 to 2.4 wt% at conditions of T=850 °C and ER=0.4	[170]
Gulf weed	No catalyst	Fixed-bed downdraft	Carbon monoxide and oxygen	900	Increasing O_2 content cause the syngas content increase at maximum value of 69.7 vol%. Decreasing feeding rate decrease the co/H_2 content.	-na-	[171]

as O_2 was added to the steam. Ismail et al. [164] investigated the effect of calcium oxide (CaO) and magnesium oxide (MgO) catalyst on the production of hydrogen in syngas for gasification of EFB. Nano scale MgO is able to enhance H_2 production, but at the same time, high amount of CO_2 was produced. Conversely the use of nano CaO showed high level production of H_2 but low CO_2 was produced. Taufiq et al. [154] utilized CaO as base catalyst but with the addition of secondary dopant lanthanum, potassium, cobalt and iron (La, K, Co, Fe). The result showed that the addition of secondary dopants significantly increased hydrogen production with notable changes in the CO_2 absorption capacity of the catalyst. Among all of the dopants, potassium, K showed the highest selectivity towards hydrogen production up to 0.03 mol compared to Fe, La and Co with 0.025 mol and below.

7. Conclusion

Syngas, consists mainly of CO and H_2, is obtained from gasification process through feedstock such as biomass, coal, refinery residual, organic waste and municipal waste. Biomass is a good source for syngas production as it is renewable, sustainable and an environmental-friendly energy source. Syngas derived from biomass has the potential to be used as alternative fuel for power generation, transportation fuels and chemical production. At present, the commonly used gasifiers include moving/fixed bed, fluidized bed, and entrained flow system. Carbon conversion rate exceeding 90% can be achieved by most gasifiers, with slight variation depending on the type of gasifiers and operating conditions. Entrained flow gasifier produces the highest quality of syngas that is clean and has low tar content compared to other gasifier types but at the expense of high operating cost. Fixed bed is a proven technology that is more cost effective but the syngas produced needs a separate cleaning process due to high content of tar. Fluidized bed is most commonly used in industry to produce syngas since it operates at medium cost and produces medium tar content. The limitation for fluidized bed is the strict requirement of complying the feedstock particle size and erosion in the systems. Transport reactor can be used to produce syngas efficiently without problems involving thermal system, syngas quality and fuel feedstock requirement.

The abundant oil palm biomass in Malaysia can potentially allow it to be the main fuel feedstock resources for syngas production. There are four main type of oil palm biomass which can be utilized as a potential feedstock for syngas; oil palm frond (OPF), empty fruit bunches (EFB), palm kernel shell (PKS) and mesocarp fiber (MF). These palm-based biomass have distinct characteristics. OPF contains the highest volatile matter content. PKS and EFB have the highest value of fixed carbon content among all palm biomass, thus exhibiting higher syngas LHV value. PKS has high ash content that could result in inferior syngas production. EFB has the highest moisture content and hence would require additional steps of drying. PKS showed high potential as feedstock to produce syngas with high LHV value and hydrogen content. Thorough understanding of the characteristics of biomass can assist in designing the suitable gasifier for optimum production of syngas.

References

[1] Maggio G, Cacciola G. When will oil, natural gas, and coal peak? Fuel 2012;98:111–23.
[2] Höök M, Tang X. Depletion of fossil fuels and anthropogenic climate change—a review. Energy Policy 2013;52:797–809.

[3] Nicoletti G, Arcuri N, Nicoletti G, Bruno R. A technical and environmental comparison between hydrogen and some fossil fuels. Energy Convers. Manage. 2015;89:205–13.

[4] Liu CC, Shy SS, Chiu CW, Peng MW, Chung HJ. Hydrogen/carbon monoxide syngas burning rates measurements in high-pressure quiescent and turbulent environment. Int J Hydrog Energy 2011;36(14):8595–603.

[5] Burbano HJ, Pareja J, Amell AA. Laminar burning velocities and flame stability analysis of H2/CO/air mixtures with dilution of N2 and CO2. Int J Hydrog Energy 2011;36(4):3232–42.

[6] Fu J, Tang C, Jin W, Thi LD, Huang Z, Zhang Y. Study on laminar flame speed and flame structure of syngas with varied compositions using OH-PLIF and spectrograph. IntJ Hydrog Energy 2013;38(3):1636–43.

[7] Shih H-Y, Hsu J-R. A computational study of combustion and extinction of opposed-jet syngas diffusion flames. Int J Hydrog Energy 2011;36 (24):15868–79.

[8] Hu E, Fu J, Pan L, Jiang X, Huang Z, Zhang Y. Experimental and numerical study on the effect of composition on laminar burning velocities of H_2/CO/N_2/CO_2/air mixtures. Int JHydrogen Energy 2012;37(23):18509–19.

[9] Chacartegui R, Sánchez D, de Escalona JMM, Monje B, Sánchez T. On the effects of running existing combined cycle power plants on syngas fuel. Fuel Process Technol 2012;103:97–109.

[10] Xu D, Lewis RS. Syngas fermentation to biofuels: effects of ammonia impurity in raw syngas on hydrogenase activity. Biomass Bioenergy 2012;45:303–10.

[11] Alauddin ZABZ, Lahijani P, Mohammadi M, Mohamed AR. Gasification of lignocellulosic biomass in fluidized beds for renewable energy development: a review. Renew Sustain Energy Rev 2010;14(9):2852–62.

[12] Speight JG. In: Inc. E, editor. Gasification of unconventional feedstocks; 2014. p. 1–29.

[13] Emami-Taba L, Irfan MF, Wan Daud WMA, Chakrabarti MH. Fuel blending effects on the co-gasification of coal and biomass – a review. Biomass Bioenergy 2013;57:249–63.

[14] Pudasainee D, Paur H-R, Fleck S, Seifert H. Trace metals emission in syngas from biomass gasification. Fuel Process Technol. 2014;120:54–60.

[15] Awalludin MF, Sulaiman O, Hashim R, Nadhari WNAW. An overview of the oil palm industry in Malaysia and its waste utilization through thermochemical conversion, specifically via liquefaction. Renew Sustain Energy Rev 2015;50:1469–84.

[16] Abdul-Manan AFN, Baharuddin A, Chang LW. A detailed survey of the palm and biodiesel industry landscape in Malaysia. Energy 2014;76:931–41.

[17] Ng WPQ, Lam HL, Ng FY, Kamal M, Lim JHE. Waste-to-wealth: green potential from palm biomass in Malaysia. J. Cleaner Prod 2012;34:57–65.

[18] Umar MS, Jennings P, Urmee T. Strengthening the palm oil biomass renewable energy industry in Malaysia. Renew Energy 2013;60:107–15.

[19] Brachi P, Chirone R, Miccio F, Miccio M, Picarelli A, Ruoppolo G. Fluidized bed co-gasification of biomass and polymeric wastes for a flexible end-use of the syngas: focus on bio-methanol. Fuel 2014;128:88–98.

[20] Grigaitienė V, Snapkauskienė V, Valatkevičius P, Tamošiūnas A, Valinčius V. Water vapor plasma technology for biomass conversion to synthetic gas. Catal Today 2011;167(1):135–40.

[21] Asadullah M. Barriers of commercial power generation using biomass gasification gas: a review. Renew Sustain Energy Rev 2014;29:201–15.

[22] Hackett GA, Gerdes K, Song X, Chen Y, Shutthanandan V, Engelhard M, Zhu Z, Thevuthasan S, Gemmen R. Performance of solid oxide fuel cells operated with coal syngas provided directly from a gasification process. J Power Sources 2012;214:142–52.

[23] Yılmaz S, Selim H. A review on the methods for biomass to energy conversion systems design. Renew Sustain Energy Rev 2013;25:420–30.

[24] Panwar NL, Kothari R, Tyagi VV. Thermo chemical conversion of biomass – eco friendly energy routes. Renew Sustain Energy Rev 2012;16(4):1801–16.

[25] Mayerhofer M, Fendt S, Spliethoff H, Gaderer M. Fluidized bed gasification of biomass – in bed investigation of gas and tar formation. Fuel 2014;117:1248–55.

[26] Robbins MP, Evans G, Valentine J, Donnison IS, Allison GG. New opportunities for the exploitation of energy crops by thermochemical conversion in Northern Europe and the UK. Prog Energy Combust Sci 2012;38(2):138–55.

[27] Bhaskar T, Bhavya B, Singh R, Naik DV, Kumar A, Goyal HB. Thermochemical conversion of biomass to biofuels: alternative feedstock and conversion processes. Elsevier Inc.; 2011. p. 51–77.

[28] Mohammed MAA, Salmiaton A, Wan Azlina WAKG, Amran MS Mohammad, Fakhru'l-Razi A, Taufiq-Yap YH. Hydrogen rich gas from oil palm biomass as a potential source of renewable energy in Malaysia. Renew Sustain Energy Rev 2011;15(2):1258–70.

[29] Couto N, Rouboa A, Silva V, Monteiro E, Bouziane K. Influence of the biomass gasification processes on the final composition of syngas. Energy Procedia 2013;36:596–606.

[30] Zhang L, Xu C, Champagne P. Overview of recent advances in thermochemical conversion of biomass. Energy Convers Manag 2010;51(5):969–82.

[31] Suopajärvi H, Pongrácz E, Fabritius T. The potential of using biomass-based reducing agents in the blast furnace: a review of thermochemical conversion technologies and assessments related to sustainability. Renew Sustain Energy Rev 2013;25:511–28.

[32] Xie Q, Borges FC, Cheng Y, Wan Y, Li Y, Lin X, Liu Y, Hussain F, Chen P, Ruan R. Fast microwave-assisted catalytic gasification of biomass for syngas production and tar removal. Bioresour Technol 2014;156:291–6.

[33] Pereira EG, da Silva JN, de Oliveira JL, Machado CS. Sustainable energy: a review of gasification technologies. Renew Sustain Energy Rev 2012;16 (7):4753–62.

[34] Xu D, Tree DR, Lewis RS. The effects of syngas impurities on syngas fermentation to liquid fuels. Biomass Bioenergy 2011;35(7):2690–6.

[35] Richardson Y, Blin J, Julbe A. A short overview on purification and conditioning of syngas produced by biomass gasification: catalytic strategies, process intensification and new concepts. Prog Energy Combust Sci 2012;38 (6):765–81.

[36] Patra TK, Sheth PN. Biomass gasification models for downdraft gasifier: a state-of-the-art review. Renew Sustain Energy Rev 2015;50:583–93.

[37] Roy PC, Datta A, Chakraborty N. An assessment of different biomass feedstocks in a downdraft gasifier for engine application. Fuel 2013;106:864–8.

[38] Mondal P, Dang GS, Garg MO. Syngas production through gasification and cleanup for downstream applications—recent developments. Fuel Process Technol 2011;2(8):1395–410.

[39] Siedlecki M, De Jong W, Verkooijen AHM. Fluidized bed gasification as a mature and reliable technology for the production of bio-syngas and applied in the production of liquid transportation fuels—a review. Energies 2011;4 (12):389–434.

[40] Richards GA, Casleton KH. Gasification technology to produce synthesis gas. In: Lieuwen T, Yang V, Yetter R, editors. Synthesis gas combustion fundamentals and applications. Taylor & Francis Group; 2010.

[41] Damartzis T, Zabaniotou A. Thermochemical conversion of biomass to second generation biofuels through integrated process design—a review. Renew Sustain Energy Rev 2011;15(1):366–78.

[42] Lee J-W, Yun Y, Chung S-W, Kang S-H, Ryu J-H, Kim G-T, Kim Y-J. Application of multiple swirl burners in pilot-scale entrained bed gasifier for short residence time. Fuel 2014;117:1052–60.

[43] Mandl C, Obernberger I, Scharler IR. Characterisation of fuel bound nitrogen in the gasification process and the staged combustion of producer gas from the updraft gasification of softwood pellets. Biomass Bioenergy 2011;35 (11):4595–604.

[44] Bocci E, Sisinni M, Moneti M, Vecchione L, Di Carlo A, Villarini M. State of art of small scale biomass gasification power systems: a review of the different typologies. Energy Procedia 2014;45:247–56.

[45] Gunarathne DS, Mueller A, Fleck S, Kolb T, Chmielewski JK, Yang W, Blasiak W. Gasification characteristics of steam exploded biomass in an updraft pilot scale gasifier. Energy 2014;71:496–506.

[46] Centeno F, Mahkamov K, Silva Lora EE, Andrade RV. Theoretical and experimental investigations of a downdraft biomass gasifier-spark ignition engine power system. Renew Energy 2012;37(1):97–108.

[47] Itai Y, Santos R, Branquinho M, Malico I, Ghesti GF, Brasil AM. Numerical and experimental assessment of a downdraft gasifier for electric power in Amazon using açaí seed (*Euterpe oleracea* Mart.) as a fuel. Renew Energy 2014;66:662–9.

[48] Martínez JD, Mahkamov K, Andrade RV, Silva Lora EE. Syngas production in downdraft biomass gasifiers and its application using internal combustion engines. Renew Energy 2012;38(1):1–9.

[49] Prasad L, Subbarao PMV, Subrahmanyam JP. Pyrolysis and gasification characteristics of Pongamia residue (de-oiled cake) using thermogravimetry and downdraft gasifier. Appl Therm Eng 2014;63(1):379–86.

[50] Boateng AA, Mtui PL. CFD modeling of space-time evolution of fast pyrolysis products in a bench-scale fluidized-bed reactor. Appl Therm Eng 2012;33–34:190–8.

[51] Galindo AL, Lora ES, Andrade RV, Giraldo SY, Jaén RL, Cobas VM. Biomass gasification in a downdraft gasifier with a two-stage air supply: effect of operating conditions on gas quality. Biomass Bioenergy 2014;61:236–44.

[52] Olgun H, Ozdogan S, Yinesor G. Results with a bench scale downdraft biomass gasifier for agricultural and forestry residues. Biomass Bioenergy 2011;35(1):572–80.

[53] Di Blasi C, Branca C. Modeling a stratified downdraft wood gasifier with primary and secondary air entry. Fuel 2013;104:847–60.

[54] Ruiz JA, Juárez MC, Morales MP, Muñoz P, Mendívil MA. Biomass gasification for electricity generation: Review of current technology barriers. Renewabl Sustainable Energy Rev 2013;18:174–83.

[55] Udomsirichakorn J, Basu P, Salam PA, Acharya B. Effect of CaO on tar reforming to hydrogen-enriched gas with in-process CO_2 capture in a bubbling fluidized bed biomass steam gasifier. Int J Hydrog Energy 2013;38 (34):14495–504.

[56] Siedlecki M, de Jong W. Biomass gasification as the first hot step in clean syngas production process – gas quality optimization and primary tar reduction measures in a 100 kW thermal input steam–oxygen blown CFB gasifier. Biomass Bioenergy 2011;35:S40–62.

[57] Matsuoka K, Hosokai S, Kuramoto K, Suzuki Y. Enhancement of coal char gasification using a pyrolyzer–gasifier isolated circulating fluidized bed gasification system. Fuel Process Technol 2013;109:43–8.

[58] Karatas H, Olgun H, Akgun F. Experimental results of gasification of cotton stalk and hazelnut shell in a bubbling fluidized bed gasifier under air and steam atmospheres. Fuel 2013;112:494–501.

[59] Bell DA, Towler BF, Fan M. Gasifiers. Coal Gasification and Its Application. Elsevier Inc.; 2011. p. 73–100.

[60] Fushimi C, Guan G, Nakamura Y, Ishizuka M, Tsutsumi A, Matsuda S, Hatano H, Suzuki Y. Hydrodynamic characteristics of a large-scale triple-bed combined circulating fluidized bed. Powder Technol 2011;209(1–3):1–8.

[61] Ngo SI, Lim Y-I, Song B-H, Lee U-D, Yang C-W, Choi Y-T, Song J-H. Hydrodynamics of cold-rig biomass gasifier using semi-dual fluidized-bed. Powder Technol 2013;234:97–106.

[62] Arromdee P, Kuprianov VI. A comparative study on combustion of sunflower shells in bubbling and swirling fluidized-bed combustors with a cone-shaped bed. Chem Eng Process 2012;62:26–38.

[63] Bahng MK, Mukarakate C, Robichaud DJ, Nimlos MR. Current technologies for analysis of biomass thermochemical processing: a review. Anal Chim Acta 2009;651(2):117–38.

[64] Meng X, Mitsakis P, Mayerhofer M, de Jong W, Gaderer M, Verkooijen AHM, Spliethoff H. Tar formation in a steam-O2 blown CFB gasifier and a steam blown PBFB gasifier (BabyHPR): Comparison between different on-line measurement techniques and the off-line SPA sampling and analysis method. Fuel Process Technol 2012;100:16–29.

[65] Yi C-K, Son J-E. Comparison of two different hot-gas desulfurization powder processes: transport reactor and bubbling fluidized bed. Adv Powder Technol 2010;21(2):119–24.

[66] Meng X, de Jong W, Fu N, Verkooijen AHM. Biomass gasification in a 100 kWth steam-oxygen blown circulating fluidized bed gasifier: Effects of operational conditions on product gas distribution and tar formation. Biomass Bioenergy 2011;35(7):2910–24.

[67] Huynh CV, Kong S-C. Combustion and NOx emissions of biomass-derived syngas under various gasification conditions utilizing oxygen-enriched-air and steam. Fuel 2013;107:455–64.

[68] Atnaw SM, Sulaiman SA, Yusup S. Syngas production from downdraft gasification of oil palm fronds. Energy 2013;61:491–501.

[69] Zhang J, Zhao Z, Zhang G, Xi Z, Zhao F, Dong L, Xu G. Pilot study on jetting pre-oxidation fluidized bed gasification adapting to caking coal. Appl Energy 2013;110:276–84.

[70] Blaszczuk A, Leszczynski J, Nowak W. Simulation model of the mass balance in a supercritical circulating fluidized bed combustor. Powder Technol 2013;246:317–26.

[71] Li T, Chaudhari K, VanEssendelft D, Turton R, Nicoletti P, Shahnam M, Guenther C. Computational fluid dynamic simulations of a pilot-scale transport coal gasifier: evaluation of reaction kinetics. Energy Fuels 2013;27(12):7896–904.

[72] Breault RW. Gasification processes old and new: a basic review of the major technologies. Energies 2010;3(2):216–40.

[73] Ogi T, Nakanishi M, Fukuda Y, Matsumoto K. Gasification of oil palm residues (empty fruit bunch) in an entrained-flow gasifier. Fuel 2013;104:28–35.

[74] Tremel A, Becherer D, Fendt S, Gaderer M, Spliethoff H. Performance of entrained flow and fluidised bed biomass gasifiers on different scales. Energy Convers Manage 2013;69:95–106.

[75] Kong X, Zhong W, Du W, Qian F. Compartment modeling of coal gasification in an entrained flow gasifier: a study on the influence of operating conditions. Energy Convers Manage 2014;82:202–11.

[76] Xu S, Ren Y, Wang B, Xu Y, Chen L, Wang X, Xiao T. Development of a novel 2-stage entrained flow coal dry powder gasifier. Appl Energy 2014;113:318–23.

[77] Chen W-H, Chen C-J, Hung C-I, Shen C-H, Hsu H-W. A comparison of gasification phenomena among raw biomass, torrefied biomass and coal in an entrained-flow reactor. Appl Energy 2013;112:421–30.

[78] Hernández JJ, Aranda-Almansa G, Bula A. Gasification of biomass wastes in an entrained flow gasifier: Effect of the particle size and the residence time. Fuel Process Technol 2010;91(6):681–92.

[79] Nguyen TDB, Lim Y-I, Song B-H, Kim S-M, Joo Y-J, Ahn D-H. Two-stage equilibrium model applicable to the wide range of operating conditions in entrained-flow coal gasifiers. Fuel 2010;89(12):3901–10.

[80] Gazzani M, Manzolini G, Macchi E, Ghoniem AF. Reduced order modeling of the Shell–Prenflo entrained flow gasifier. Fuel 2013;104:822–37.

[81] Zhou J, Chen Q, Zhao H, Cao X, Mei Q, Luo Z, Cen K. Biomass-oxygen gasification in a high-temperature entrained-flow gasifier. Biotechnol Adv 2009;27(5):606–11.

[82] Senapati PK, Behera S. Experimental investigation on an entrained flow type biomass gasification system using coconut coir dust as powdery biomass feedstock. Bioresour Technol 2012;117:99–106.

[83] Plis P, Wilk RK. Theoretical and experimental investigation of biomass gasification process in a fixed bed gasifier. Energy 2011;36(6):3838–45.

[84] Patil K, Bhoi P, Huhnke R, Bellmer D. Biomass downdraft gasifier with internal cyclonic combustion chamber: design, construction, and experimental results. Bioresour Technol 2011;102(10):6286–90.

[85] Raman P, Ram NK, Gupta R. A dual fired downdraft gasifier system to produce cleaner gas for power generation: design, development and performance analysis. Energy 2013;54:302–14.

[86] Jordan CA, Akay G. Effect of CaO on tar production and dew point depression during gasification of fuel cane bagasse in a novel downdraft gasifier. Fuel Process Technol 2013;106:654–60.

[87] Lahijani P, Zainal ZA. Gasification of palm empty fruit bunch in a bubbling fluidized bed: a performance and agglomeration study. Bioresour Technol 2011;102(2):2068–76.

[88] Thunman H, Lind F, Breitholtz C, Berguerand N, Seemann M. Using an oxygen-carrier as bed material for combustion of biomass in a 12-MWth circulating fluidized-bed boiler. Fuel 2013;113:300–9.

[89] Guío-Pérez DC, Pröll T, Hofbauer H. Influence of ring-type internals on the solids residence time distribution in the fuel reactor of a dual circulating fluidized bed system for chemical looping combustion. Chem Eng Res Des 2014;92(6):1107–18.

[90] Ngo SI, Nguyen TDB, Lim Y-I, Song B-H, Lee U-D, Choi Y-T, Song J-H. Performance evaluation for dual circulating fluidized-bed steam gasifier of biomass using quasi-equilibrium three-stage gasification model. Appl Energy 2011;88(12):5208–20.

[91] Christodoulou C, Grimekis D, Panopoulos KD, Vamvuka D, Karellas S, Kakaras E. Circulating fluidized bed gasification tests of seed cakes residues after oil extraction and comparison with wood. Fuel 2014;132:71–81.

[92] Xiao X, Le DD, Morishita K, Zhang S, Li L, Takarada T. Multi-stage biomass gasification in Internally Circulating Fluidized-bed Gasifier (ICFG): Test operation of animal-waste-derived biomass and parametric investigation at low temperature. Fuel ProcessTechnol 2010;91(8):895–902.

[93] Masmoudi MA, Sahraoui M, Grioui N, Halouani K. 2-D Modeling of thermo-kinetics coupled with heat and mass transfer in the reduction zone of a fixed bed downdraft biomass gasifier. Renew Energy 2014;66:288–98.

[94] Qin K, Lin W, Jensen PA, Jensen AD. High-temperature entrained flow gasification of biomass. Fuel 2012;93:589–600.

[95] Hernández JJ, Aranda G, Barba J, Mendoza JM. Effect of steam content in the air–steam flow on biomass entrained flow gasification. Fuel Process Technol. 2012;99:43–55.

[96] Kaewluan S, Pipatmanomai S. Gasification of high moisture rubber woodchip with rubber waste in a bubbling fluidized bed. Fuel Process Technol 2011;92(3):671–7.

[97] Cordiner S, De Simone G, Mulone V. Experimental–numerical design of a biomass bubbling fluidized bed gasifier for paper sludge energy recovery. Appl Energy 2012;97:532–42.

[98] Guan G, Fushimi C, Ishizuka M, Nakamura Y, Tsutsumi A, Matsuda S, Suzuki Y, Hatano H, Cheng Y, Chuan Lim EW, Wang C-H. Flow behaviors in the downer of a large-scale triple-bed combined circulating fluidized bed system with high solids mass fluxes. Chem Eng Sci 2011;66(18):4212–20.

[99] Antonopoulos IS, Karagiannidis A, Gkouletsos A, Perkoulidis G. Modelling of a downdraft gasifier fed by agricultural residues. Waste Manag 2012;32(4):710–8.

[100] Umar MS, Jennings P, Urmee T. Generating renewable energy from oil palm biomass in Malaysia: the Feed-in Tariff policy framework. Biomass Bioenergy 2014;62:37–46.

[101] Kunze C, Spliethoff H. Modelling, comparison and operation experiences of entrained flow gasifier. Energy Convers Manage 2011;52(5):2135–41.

[102] Gabrielle B, Bamière L, Caldes N, De Cara S, Decocq G, Ferchaud F, Loyce C, Pelzer E, Perez Y, Wohlfahrt J, Richard G. Paving the way for sustainable bioenergy in Europe: Technological options and research avenues for large-scale biomass feedstock supply. Renew Sustain Energy Rev 2014;33:11–25.

[103] Malaysia energy statistics handbook, 2015. Malaysia: Putrajaya; 2015.

[104] Yusoff S, Kardooni R. Barriers and challenges for developing RE policy in Malaysia. In: 2012 International Conference on Future Environment and Energy IPCBEE. Singapore: IACSIT Press; 2012.

[105] Hashim H, Ho WS. Renewable energy policies and initiatives for a sustainable energy future in Malaysia. Renew Sustain Energy Rev 2011;15(9):4780–7.

[106] Shafie SM, Mahlia TMI, Masjuki HH, Ahmad-Yazid A. A review on electricity generation based on biomass residue in Malaysia. Renew Sustain Energy Rev 2012;16(8):5879–89.

[107] Sovacool BK, Drupady IM. Examining the Small Renewable Energy Power (SREP) Program in Malaysia. Energy Policy 2011;39(11):7244–56.

[108] Umar MS, Jennings P, Urmee T. Sustainable electricity generation from oil palm biomass wastes in Malaysia: an industry survey. Energy 2014;67:496–505.

[109] Mekhilef S, Saidur R, Safari A. and Mustaffa WESB. Biomass energy in Malaysia: Current state and prospects. Renew Sustain Energy Rev 2011;15(7):3360–70.

[110] Ali R, Daut I, Taib S. A review on existing and future energy sources for electrical power generation in Malaysia. Renew Sustain Energy Rev 2012;16(6):4047–55.

[111] MALAYSIA international energy data and analysis: U.S. Energy Information and Administration. Available from: ⟨https://www.eia.gov/beta/international/analysis.cfm?iso=MYS#note⟩ [cited 03.01.16].

[112] Shamsuddin AH. Development of Renewable Energy in Malaysia—strategic initiatives for carbon reduction in the power generation sector. Procedia Eng 2012;49:384–91.

[113] Kardooni R, Yusoff SB, Kari FB. Renewable energy technology acceptance in Peninsular Malaysia. Energy Policy 2016;88:1–10.

[114] Raman P, Ram NK. Performance analysis of an internal combustion engine operated on producer gas, in comparison with the performance of the natural gas and diesel engines. Energy 2013;63:317–33.

[115] Roni MS, Eksioglu SD, Searcy E, Jha K. A supply chain network design model for biomass co-firing in coal-fired power plants. Transp Res Part E: Logist Transp Rev 2014;61:115–34.

[116] Iribarren D, Susmozas A, Dufour J. Life-cycle assessment of Fischer–Tropsch products from biosyngas. Renew Energy 2013;59:229–36.

[117] Ng KS, Sadhukhan J. Techno-economic performance analysis of bio-oil based Fischer-Tropsch and CHP synthesis platform. Biomass Bioenergy 2011;35(7):3218–34.

[118] Shimura K, Miyazawa T, Hanaoka T, Hirata S. Factors influencing the activity of Co/Ca/TiO2 catalyst for Fischer–Tropsch synthesis. Catal. Today 2014;232:2–10.

[119] Schulz H. Selforganization in Fischer–Tropsch synthesis with iron- and cobalt catalysts. Catal. Today 2014;228:113–22.

[120] Darshini D, Dwivedi P, Glenk K. Capturing stakeholders´ views on oil palm-based biofuel and biomass utilisation in Malaysia. Energy Policy 2013;62:1128–37.

[121] Cheng SF, Nor LM, Chuah CH. Microwave pretreatment: a clean and dry method for palm oil production. Ind. Crops Prod. 2011;34(1):967–71.

[122] Guangul FM, Sulaiman SA, Ramli A. Gasifier selection, design and gasification of oil palm fronds with preheated and unheated gasifying air. Bioresour Technol 2012;126:224–32.

[123] Ashnani MHM, Johari A, Hashim H, Hasani E. A source of renewable energy in Malaysia, why biodiesel? Renew Sustain Energy Rev 2014;35:244–57.

[124] Hoong SS. Palm Oil and Related Products. 1 of 12 National Key Economic Areas under Economic Transformation Programme; 2011. pp. 11–15.

[125] Abas R, Kamarudin MF, Nordin ABA, Simeh MA. A study on the Malaysian oil palm biomass sector – supply and perception of palm oil millers. Oil Palm Ind Econ J 2011;11(1):28–41.

[126] Abnisa F, Daud WMAW, Husin WNW, Sahu JN. Utilization possibilities of palm shell as a source of biomass energy in Malaysia by producing bio-oil in pyrolysis process. Biomass Bioenergy 2011;35(5):1863–72.

[127] Er AC, Nor ARM, Rostam K. Palm oil milling wastes and sustainable development. Am J Appl Sci 2011;8(5):436–40.

[128] Shafawati SN, Siddiquee S. Composting of oil palm fibres and Trichoderma spp. as the biological control agent: a review. Int Biodeterior Biodegrad 2013;85:243–53.

[129] Chin MJ, Poh PE, Tey BT, Chan ES, Chin KL. Biogas from palm oil mill effluent (POME): opportunities and challenges from Malaysia's perspective. Renew Sustain Energy Rev 2013;26:717–26.

[130] Erlich C, Fransson TH. Downdraft gasification of pellets made of wood, palm-oil residues respective bagasse: experimental study. Appl Energy 2011;88(3):899–908.

[131] Sulaiman F, Abdullah N, Gerhauser H, Shariff A. An outlook of Malaysian energy, oil palm industry and its utilization of wastes as useful resources. Biomass Bioenergy 2011;35:3775–86.

[132] Hansen UE, Nygaard I. Sustainable energy transitions in emerging economies: the formation of a palm oil biomass waste-to-energy niche in Malaysia 1990–2011. Energy Policy 2014;66:666–76.

[133] Bazmi AA, Zahedi G, Hashim H. Progress and challenges in utilization of palm oil biomass as fuel for decentralized electricity generation. Renew Sustain Energy Rev 2011;15(1):574–83.

[134] Mohammed MA, Salmiaton A, Wan Azlina WA, Mohamad Amran MS. Gasification of oil palm empty fruit bunches: a characterization and kinetic study. Bioresour Technol 2012;110:628–36.

[135] Sluiter JB, Ruiz RO, Scarlata CJ, Sluiter AD, Templeton DW. Compositional analysis of lignocellulosic feedstocks. 1. Review and description of methods. J Agric Food Chem 2010;58(16):9043–53.

[136] Saidur R, Abdelaziz EA, Demirbas A, Hossain MS, Mekhilef S. A review on biomass as a fuel for boilers. Renew Sustain Energy Rev 2011;5(5):2262–89.

[137] Chiesa S, Gnansounou E. Use of Empty Fruit Bunches from the oil palm for bioethanol production: a thorough comparison between dilute acid and dilute alkali pretreatment. Bioresour Technol 2014;159:355–64.

[138] Harsono SS, Grundman P, Lau LH, Hansen A, Salleh MAM, Meyer-Aurich A, Idris A, Ghazi TIM. Energy balances, greenhouse gas emissions and economics of biochar production from palm oil empty fruit bunches. Resour Conserv Recycl 2013;77:108–15.

[139] Demirbas A. Fuels from biomass. biorefineries for biomass upgrading facilities. Springer; 2010.

[140] Omar R, Idris A, Yunus R, Khalid K, Aida Isma MI. Characterization of empty fruit bunch for microwave-assisted pyrolysis. Fuel 2011;90(4):1536–44.

[141] Abdullah N, Sulaim F. The Oil Palm Wastes in Malaysia. 2013.

[142] Parshetti GK, Kent Hoekman S, Balasubramanian R. Chemical, structural and combustion characteristics of carbonaceous products obtained by hydrothermal carbonization of palm empty fruit bunches. Bioresour Technol 2013;135:683–9.

[143] Ninduangdee P, Kuprianov VI. Study on burning oil palm kernel shell in a conical fluidized-bed combustor using alumina as the bed material. J. Taiwan Inst Chem Eng 2013;44(6):1045–53.

[144] Kristiani A, Abimanyu H, Setiawan AH, Sudiyarmanto, Aulia F. Effect of pretreatment process by using diluted acid to characteristic of oil Palm's Frond. Energy Procedia 2013;32:183–9.

[145] Abnisa F, Arami-Niya A, Wan Daud WMA, Sahu JN, Noor IM. Utilization of oil palm tree residues to produce bio-oil and bio-char via pyrolysis. Energy Convers Manag 2013;76:1073–82.

[146] Abu Bakar MS, Titiloye JO. Catalytic pyrolysis of rice husk for bio-oil production. J Anal Appl Pyrolysis 2013;103:362–8.

[147] Dascomb J, Krothapalli A, Fakhrai R. Thermal conversion efficiency of producing hydrogen enriched syngas from biomass steam gasification. Int J Hydrog Energy 2013;38(27):11790–8.

[148] Burhenne L, Messmer J, Aicher T, Laborie M-P. The effect of the biomass components lignin, cellulose and hemicellulose on TGA and fixed bed pyrolysis. J Anal Appl Pyrolysis 2013;101:177–84.

[149] Garcia-Maraver A, Salvachua D, Martinez MJ, Diaz LF, Zamorano M. Analysis of the relation between the cellulose, hemicellulose and lignin content and the thermal behavior of residual biomass from olive trees. Waste Manag 2013;33(11):2245–9.

[150] Moghadam RA, Yusup S, Uemura Y, Chin BLF, Lam HL, Al Shoaibi A. Syngas production from palm kernel shell and polyethylene waste blend in fluidized bed catalytic steam co-gasification process. Energy 2014;75:40–4.

[151] Khan Z, Yusup S, Ahmad MM, Rashidi NA. Integrated catalytic adsorption (ICA) steam gasification system for enhanced hydrogen production using palm kernel shell. Int J Hydrog Energy 2014;39(7):3286–93.

[152] Aziz M, Prawisudha P, Prabowo B, Budiman BA. Integration of energy-efficient empty fruit bunch drying with gasification/combined cycle systems. Applie Energy 2015;139:188–95.

[153] Sivasangar S, Zainal Z, Salmiaton A, Taufiq-Yap YH. Supercritical water gasification of empty fruit bunches from oil palm for hydrogen production. Fuel 2015;143:563–9.

[154] Taufiq-Yap YH, Sivasangar S, Salmiaton A. Enhancement of hydrogen production by secondary metal oxide dopants on NiO/CaO material for catalytic gasification of empty palm fruit bunches. Energy 2012;47(1):158–65.

[155] Bazargan A, Kostić MD, Stamenković OS, Veljković VB, McKay G. A calcium oxide-based catalyst derived from palm kernel shell gasification residues for biodiesel production. Fuel 2015;150:519–25.

[156] Asadullah M, Adi AM, Suhada N, Malek NH, Saringat MI, Azdarpour A. Optimization of palm kernel shell torrefaction to produce energy densified bio-coal. Energy Convers Manag 2014;88:1086–93.

[157] Asadullah M, Ab Rasid NS, Kadir SASA, Azdarpour A. Production and detailed characterization of bio-oil from fast pyrolysis of palm kernel shell. Biomass Bioenergy 2013;59:316–24.

[158] Dong L, Asadullah M, Zhang S, Wang X-S, Wu H, Li C-Z. An advanced biomass gasification technology with integrated catalytic hot gas cleaning. Fuel 2013;108:409–16.

[159] Nipattummakul N, Ahmed II N, Gupta AK, Kerdsuwan S. Hydrogen and syngas yield from residual branches of oil palm tree using steam gasification. Int J Hydrog Energy 2011;36(6):3835–43.

[160] Mendiburu AZ, Carvalho JA, Coronado CJR. Thermochemical equilibrium modeling of biomass downdraft gasifier: Stoichiometric models. Energy 2014;66:189–201.

[161] Xie Q, Kong S, Liu Y, Zeng H. Syngas production by two-stage method of biomass catalytic pyrolysis and gasification. Bioresour Technol 2012;110:603–9.

[162] Zou W, Song C, Xu S, Lu C, Tursun Y. Biomass gasification in an external circulating countercurrent moving bed gasifier. Fuel 2013;112:635–40.

[163] Mohammed AS MAA, Wan Azlina WAKG, Amran MS Mohammad, Fakhru'l-Razi A. Air gasification of empty fruit bunch for hydrogen-rich gas production in a fluidized-bed reactor. Energy Convers Manage 2011;52:1555–61.

[164] Ismail K, Yarmo MA, Taufiq-Yap YH, Ahmad A. The effect of particle size of CaO and MgO as catalysts for gasification of oil palm empty fruit bunch to produce hydrogen. Int J Hydrog Energy 2012;3(7):3639–44.

[165] Kalinci Y, Hepbasli A, Dincer I. Comparative exergetic performance analysis of hydrogen production from oil palm wastes and some other biomasses. Int J Hydrog Energy 2011;36(17):11399–407.

[166] Xiao X, Cao J, Meng X, Le DD, Li L, Ogawa Y, Sato K, Takarada T. Synthesis gas production from catalytic gasification of waste biomass using nickel-loaded brown coal char. Fuel 2013;103:135–40.

[167] Hurley S, Xu C, Preto F, Shao Y, Li H, Wang J, Tourigny G. Catalytic gasification of woody biomass in an air-blown fluidized-bed reactor using Canadian limonite iron ore as the bed material. Fuel 2012;91(1):170–6.

[168] Luo S, Xiao B, Hu Z, Liu S, Guo X, He M. Hydrogen-rich gas from catalytic steam gasification of biomass in a fixed bed reactor: Influence of temperature and steam on gasification performance. Int J Hydrog Energy 2009;34(5):2191–4.

[169] Corujo A, Yermán L, Arizaga B, Brusoni M, Castiglioni J. Improved yield parameters in catalytic steam gasification of forestry residue; optimizing biomass feed rate and catalyst type. Biomass Bioenergy 2010;34(12):1695–702.

[170] Skoulou VK, Zabaniotou AA. Co-gasification of crude glycerol with lignocellulosic biomass for enhanced syngas production. J Anal Appl Pyrolysis 2013;99:110–6.

[171] Hanaoka T, Hiasa S, Edashige Y. Syngas production by CO_2/O_2 gasification of aquatic biomass. Fuel Process Technol 2013;116:9–15.