

Gasification of Non-woody Biomass: a Literature Review

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Abstract

Non-woody biomass, having lower cellulose content than woody materials, is a common waste material found in agricultural processing plants and fields. Non-woody biomass is often bulky and has a comparatively low energy content. However, non-woody materials sourced from agricultural waste are abundant and cheap. Experimental studies into gasification of non-woody biomass have been conducted by various researchers. This paper reviews feedstock characteristics, pre-treatments, gasification methods, and future direction of this technology. Due to the heterogeneous nature of non-woody biomass, it is critical to apply suitable pre-treatments prior to gasification. Combining non-woody biomass with a small percentage of high grade carbon sourced from biochar or coal into fuel pellets for co-gasification has the potential to improve fuel quality. Synergistic effects of non-woody biomass-charcoal co-gasification can also reduce tar formation and increase the occurrence of mineral based catalytic reactions. Factors influencing these effects are often complex and require further investigation. 15-20% of fuel pellets energy content may be needed to power the biomass pre-treatment process. The gasification of pelletised non-woody waste provides an attractive alternative fuel source to achieve agricultural energy self-sufficiency and off-grid operation.

Keywords: non-woody, biomass, densification, gasification, co-gasification

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1 Introduction

Non-woody biomass has a lower cellulose content than woody biomass sources and may often be categorised as waste. This type of biomass may come from a wide range of agricultural processes, animal wastes and herbaceous plants. Common examples of non-woody biomass from agricultural processing plants may include biomass wastes such as cotton gin trash (CGT), palm oil waste, cane bagasse and animal paunch waste. On the other hand, paddy husks, straw, grasses, crop stubble and trash are typical agricultural field waste.

Non-woody agricultural waste is usually abundant, readily available and relatively cheap. For example, one hectare of cotton farm in Australia may typically produce 1.6 tonne of cotton lint and 2.5 tonne of cotton seed (by-product). In the same time, it may also generate about 2 tonnes of straw and 0.4 tonne of cotton gin waste [1]. Abundant amounts of wheat and barley straw and chaff are also produced every year. In average, Australia produces some 25 million tonnes of wheat and 8 million tonnes of barley every year. The typical straw to grain ratios for wheat and barley are respectively 1:1 and 0.7:1. These also produce a significant amount of non-woody biomass waste.

The disposal of agricultural waste often faces significant environmental problems and associated health issues. Currently in Australia, cotton stalk wastes are usually returned to the field to increase the soil organic matter. A common practice of managing cotton gin waste is also by composting. However, this option often faces the problems of low market demand and also possible pathogen contamination concerns within the composted product [1].

Recycling the waste to generate energy is another option. For example, the cotton gin waste can be recycled into energy source to meet the energy demand in ginning plants. This method also does not require extra cost of transportation. This practice has also been used in other industries such as sugarcane and palm oil processing plants whereas bagasse and oil palm husk have been recycled as fuel in the combined heat and power systems. However, the current utilization in combustion systems often only achieves low efficiency energy conversion. As the non-woody biomass has the characteristics of low density, low quality as

solid fuel and with varying properties, improving the energy conversion efficiency of the non-woody biomass remains a significant challenge.

The process of energy conversion can be divided into biological and thermochemical processes. Biological processes that include fermentation into ethanol and anaerobic digestion into methane gas face the challenge of some feedstock having a low lignocellulosic conversion rate. Thermochemical processes can be categorized into pyrolysis, combustion and gasification. Pyrolysis which produces bio-oil has limitations in oil utilization and difficulty in the downstream oil processing. Biomass combustion, which usually generates a considerable amount of heat and power for the process industry, has low energy conversion efficiency, high gaseous and particulate pollution and has to compete with established coal based technologies. Another thermochemical process is gasification. It converts biomass through a high temperature limited oxidation pyrolysis-like process into a gaseous mixture, producing a small quantity of char and condensable compounds. This method is often considered the most efficient way of converting lignocellulose material into gas based energy, with typical conversion efficiencies of higher than 50% [2]. Gasification has been intensively studied for a wide range of biomass materials.

For non-woody biomass, the main steps of gasification are usually:

- Measuring the properties of the feedstock
- Pre-treatment of the feedstock for effective gasification system use
- Gasification of biomass.

Compared with woody biomass, there is currently a lower utilisation of energy production from non-woody sources. This is because non-woody material has a lower energy content and varying physical properties. Of . The methods of gasification for non-woody materials can be further categorised into two approaches, firstly by improving or selecting the optimal design of gasifier and secondly by upgrading the fuel to be compatible with the reactor.

This paper reviews the potential applications and challenges of the use of non-woody biomass for gasification. The future direction of the non-woody gasification will also be discussed. In off-grid areas of rural agriculture such as regularly found in developing countries, the energy needs of agricultural processing, household power and waste management are often high.

2 Non-woody biomass properties as solid fuel

Solid fuel compositions are typically characterised by proximate and ultimate analyses. Proximate analysis characterises the fuel in terms of fixed carbon, moisture, ash and volatile matter. Ultimate analysis indicates levels of the main chemical elements (C, H, O, N, S) from which thermochemical reactions take place. During these thermochemical processes, the mineral contents are converted into ash, which is a generally inert material that reduces the effective energy value of a feedstock. Due to higher ash and tar contents, the non-woody biomass gasification process faces technical issues of ash sintering, tar collection and bed bridging [3, 4].

Table 1 shows the fuel properties of non-woody biomass in comparison with charcoal (coal & bio-char) and woody biomass. The higher carbon content in solid fuel leads to higher energy content. In contrast, higher moisture and ash in non-woody biomass would decrease the energy content. However, the carbon component is not the only factor influencing gasification. The elements of hydrogen and oxygen from the moisture and oxidants in the gasification process will generally also react to produce hydrogen, methane and CO gas components in the resulting syngas composition. An additional issue with non-woody biomasses is that they generally have low densities, particularly for sources originating from herbaceous plants. This can cause difficulties in handling during gasification, particularly in controlling the fuel flow rate.

The mineral materials found in biomass mainly comprise of alkali (potassium, sodium), alkaline earth (calcium, magnesium) and other minerals such as Fe, Si, Al, Cl and P. These materials can potentially form ash during the thermochemical conversion process. Some alkali and alkaline earth may also help the reactions as a catalyst in gasification. However, these mineral materials can react with silica to form alkali silicate, which may be occasionally found significantly high in non-woody materials. The problem with high ash content of non-woody biomass can also cause agglomeration in the gasifier or combustor bed [5, 6].

3 Pre-treatment

The objective of pretreatment is to create the biomass suitable as a feedstock for gasification systems. Because of a wide range of properties of non-woody biomass, the pre-treatment system can become a critical aspect of minimizing failure in gasification process. The pre-treatment of feedstock includes one or a combined process of size reduction, drying and densification.

3.1 *Size reduction*

Size reduction is often required to obtain an appropriate particle size. The irregular shape and size along with the varied composition found in non-woody biomass often requires size reduction. This is necessary for providing a uniform size for gasification or for the next pretreatment process step such as pelleting. In general, smaller particles have larger surface areas and pore sizes, allowing faster reactions and better heat transfer. The common particle size range of gasification feedstock is 1µm to 1cm [7]. The required size of feedstock is also dependent upon the type of gasifier used. The fluidized bed gasifier usually requires the feedstock to be sized for easy fluidization to maximize the contact of the feedstock particle surface with the oxidant. The entrained bed type requires finer particles. On the contrary, fixed bed gasifiers require larger particle sizes, of the order of 1cm, as a slower reduction is required. This is for the purpose of delaying the process of rapid combustion while allowing effective de-volatilization.

Equipment for size reduction can include hammer mills, rotary knife cutters or grinders. Energy consumption of this equipment depends on moisture content, size reduction ratio and biomass properties such as fibre content. For fibrous materials, Souza-Santos 2010[7] suggested using knife cutters instead of grinders, as many grinding processes dramatically increase the fraction of particles having broom-like ends. This kind of feedstock can become entangled, leading to agglomeration in the feeding system.

3.2 *Drying*

Non-woody biomass from a processing plant or from the field often has high moisture content. Drying is typically required for reducing moisture content to 10-15% [8]. Low moisture content biomass, such as cotton gin waste, does not require drying. However, paunch waste having a moisture content of higher than 50% would require drying in its pre-processing stage. Drying can be an energy intensive task which can negatively reduce the overall efficiency of energy production. Each kilogram of moisture requires about 2300 kJ for vaporization [8]. The energy for drying can however be recovered from the heat generated during the process of gasification or achieved with other renewable means such as solar heating.

3.3 *Densification*

Non-woody biomass often has a low bulk density, irregular shape and size. This is one of the main difficulties of handling, storing and applying non-woody biomass in its' original

form. Densification can be a solution as a pre-treatment of non-woody biomass for use as a solid fuel. There are generally two methods of feedstock densification: torrefaction and pelleting [9, 10]. Densification not only increases the density but can also improve the efficiency of the thermochemical conversion process as follows.

Torrefaction is achieved by heating biomass at moderate temperatures (200-300°C) in an inert atmosphere. It can increase the mass density and energy density of the fuel [11]. It can also reduce moisture content, volatiles and the level of mineral content in which the mineral oxide present may cause slagging or caking ash in the combustion zone [12]. Studies on biomass torrefaction as pre-treatment for gasification have been conducted by Samy 2013[9] using cotton gin trash (CGT). The comparison of raw and the torrefied CGT gasification showed that the torrefied CGT generally achieve higher carbon conversion and gasification efficiency. However, by simply increasing the temperature of the reactor from 850 to 950°C the reaction rate of raw CGT gasification was greatly improved. By increasing the reactor temperature, the carbon conversion and cold gas efficiency of the raw CGT was close to that achieved with the torrefied process. At 950°C, the carbon conversion of both raw and torrefied processes reached 55%.

Torrefaction and pelleting can increase the devolatilisation rates. Sarkar *et al.*, 2014[11] compared the devolatilisation kinetics of switchgrass that was torrefied, torrefied and pelleted or raw-pelleted as pre-treatment processes. In both inert and oxidising atmospheres, the highest devolatilisation rates were achieved with post-torrefied pellets, followed by raw-pelleted and finally raw-torrefied biomass. The research showed that the pelleting process increased devolatilisation for both raw and torrefied materials.

Torrefied pellets show promise as a pre-treatment technology for solid fuel applications. Uslu *et al.*, 2008[13], studied solid fuel production by the three processes mentioned above and found that energy densities of the torrefied, torrefied and pelleted and raw-pelleted biomass of 4.6 GJ/m³, 14.9-18.4 GJ/m³ and 7.8-10.5 GJ/m³ respectively. The research further reported that the raw torrefied biomass in this study had the highest energy production efficiency. However, it was also noted that the data was not taken from a commercial plant for the torrefied product. Furthermore, the raw torrefied biomass had the lowest energy density, highest energy input and transportation cost. Uslu *et al.*, 2008[13] thus recommended that the torrefied pellet could be the best option in the international bioenergy supply chain.

Pelleting or briquetting is another method of densification. The initial objective of pelleting or briquetting the non-woody biomass is to increase density. A particle size of about 1-2 cm in the form of pellet is often best for simple biomass gasifiers of fixed bed design.

The biomass pellet, particularly the wood pellet from wood waste has been available commercially for many years. The main function of pelleting is predominantly to densify the biomass, but it can also increase the efficiency of thermochemical conversion. In the pellet form, non-woody biomass combustion can produce lower ash content compared to raw material. Holt *et al.*, 2006[14], reported that the ash content of combusting cotton gin waste pellets was decreased two to three fold compared to combusting the unpelleted material. Upgrading the biomass feedstock into a pelleted form may also be desirable for industrial heating systems, particularly in regards to the infeed system operation. This is because the pellet combustion/gasification can be easier to control than with comparable raw biomass infeed systems. The irregular shape and size of raw non-woody biomass are often the cause of entangled ‘clumps’ in the feeding system. This can cause unstable combustion or gasification with increased emissions and lower overall efficiency. In a pelleted form, controls are of a comparable level to that of a liquid/gas fuelled system. The similar size, water content and particle density may make it easier for automated operation [15]

Wood pellets have been successful in domestic heating applications in the USA and European countries. The standard quality attributes of the fuel pellets for both regions has been based generally on the total ash content and durability [14,16, 17]. However, another lower grade category of fuel pellet for industrial purposes has been also considered [15]. Industries may need to have more adaptable equipment and use a flexible emission control system in order to cater for the lower fuel quality whilst keeping emissions at an acceptable level. This grade of the fuel pellet can be sourced from standard non-woody biomass and Refuse-Derived Fuel (RDF).

A summary of recent studies on biomass pelleting is presented in Table 2. Although wood pellets from waste has been available commercially for some time, the wide variation of biomass properties requires specific studies for the development of appropriate pelleting processes for each range of feedstocks. Essentially, the biomass pelleting process is a method of compressing the raw materials. The standard equipment used for this process is a screw extruder or a roller-plate, die pellet-mill. The efficiency of the equipment depends on die temperature, die and roller configuration, pressure, feed rate and moisture content and properties of the feedstock [13, 14]. Recent studies have looked into the effect of binder addition or additive materials along with the treatment effects of extrusion temperature, pressure and moisture content. These studies primarily looked into the quality of the developed fuel pellet and associated biomass properties.

In general, natural lignin, protein, starch and water soluble carbohydrate may act as a pellet binder [18]. Lignocellulosic materials have lignin bonded in the form of a lignocellulosic matrix. The softening, flow and subsequent hardening of lignin in the process of pelleting are similar in nature to a bonding process. The applied pressure combined with elevated temperature at which the polymer softens and passes from a glassy into a plastic form are the key factors of pelleting biomass. As each non-woody biomass has its own particular lignocellulosic composition and bonding structure, sometimes a pre-treatment of fractionation of the lignin bonds, cellulose and hemicellulose is required prior to pressing. This is for the purpose to generate uniform durability and stable structure of the produced pellet. The fractionation method can be either one or combined processes of steam explosion, acid/alkali treatment and biological fermentation [19]. At the industrial scale, the established technology of steam explosion is often applied. It applies steam at the ranging temperatures of 180-240°C to rupture the cellular structure [20]. The biological fermentation is promising but still challenging in reaching the efficient colder process application in the large scale industries [19]. Occasionally the fractionation is still inadequate for the non-woody biomass pelleting [21]. Binder or other additives can be added to improve the strength, the durability and the thermochemical properties of the pellet. Additional starch, bentonite, lignosulfonate may further improve the mechanical structure of the pellet.

The Idea of upgrading pellet fuel heating value and thermochemical properties by addition of some substances during the pelleting process has also been investigated [14, 18, 22]. It was found that additional calcium based catalysts, oils and glycerol in the pelleting process could increase the fuel properties and overall efficiency of thermochemical process. However, addition of these substances can sometimes cause negative effects in pellet durability and lowering the density, e.g. addition of oil to cotton gin trash [14]. Studies in this area are on-going.

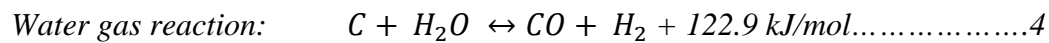
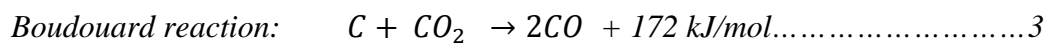
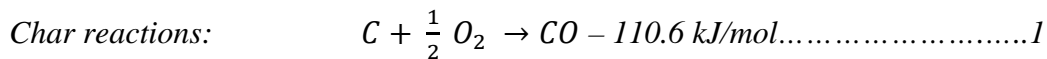
4 Gasification

Gasification is a thermochemical conversion process which involves various chemical reactions, heat and mass transfer and also pressure. This technology has been used in 1800's for gas production from coal. In the 1900's wood gasification was used in Europe for fuelling cars. Previously, the gasification of solid fuel was aimed at generating energy in the form of combustible syngas. Lately, this process is also used to convert the liquid fractions into gases or chemicals [23]. The gas produced from gasification is usually called syngas or producer gas, comprised of combustible gases of CO, H₂ and CH₄ and a significant amount of the inert

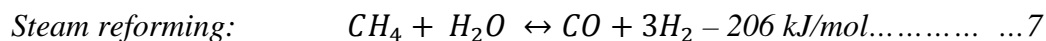
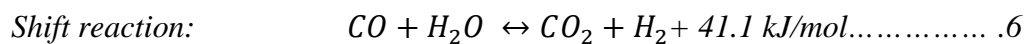
gas of CO₂. If the gasifying agent is air, then a significant amount of N₂ can also be present. The typical calorific value of the syngas produced from biomass is about 4-10 MJ/m³ with the carbon conversion efficiency circa 50-70% [24, 25].

Thermochemical conversion of the solid fuel in gasification is a complex chemical and physical process which can be summarized as below:

- Vaporization: the early stage of heating applied, the water content will be vaporized.
- Devolatilization/pyrolysis: the devolatilization process begins when the biomass temperature reaches a critical level. The products are char and volatiles. The volatiles are in form of high density liquid (tar) and a small amount of gases.
- Secondary cracking tar: tar is a mixture of condensable hydrocarbons. The heat may crack the tar. The cracking causes some homogenous reactions in the gas phase and heterogeneous ones at surface of solid fuel or char particles
- Reactions/reduction/gasification: char as the devolatilization residue will react with the gas species as heterogeneous reactions.



The devolatilisation gas and cracking gas species will be also reacted with the oxidant and among other species as homogenous reactions. The heat generated is used for the release of volatiles and char ignition.



Gasifier is the reactor for gasification process. The type of gasifier is often classified by the flow condition of fuel and gas. The fixed bed is the simplest technology whereas the fuel flows naturally as thorough the processes of drying, pyrolysis, gasification and combustion controlled only by oxidant and fuel amount [26]. The fixed bed type is also known as moving bed as the particle is moving through the beds of drying, pyrolysis, gasification and combustion, though in practice no exact boundary exists between each zone [7]. The fixed bed allows the intimate contact of fuel particles and gases. The fluidised bed fluidises the fuel for achieving more contact between fuel and oxidiser for the reactions. The entrained bed

type has even lesser particle contact, as the fuel particle is finer feeding by atomiser conditioned for high surface contact with oxidiser. Under these general three categories, there are two sub types for fixed bed and fluidised bed. This is summarized in Table 3. Depending upon the source of heating, the reactor heat can be categorised either as allo-thermal if the heating is sourced from external, or it is known as an auto-thermal if the heat is sourced from partial combustion of the fuel. For small to medium scale, a fixed bed is usually the simplest, auto-thermal and so less energy input is required.

Studies in the non-woody biomass gasification have been conducted by many researchers (Table 4). Because of the different properties of non-woody, the method of gasification approach may be examined from two aspects; firstly the selection of suitable gasifier design and secondly the approach of upgrading the feedstock quality.

4.1 Selection of suitable gasifier design for non woody biomass gasification

The issue of managing the biomass density problems of non-woody biomass can be partially mitigated by the appropriate selection of the gasifying method. Applying less pre-treatment regimes e.g. only size reduction is often suitable for fluidised, pressurised or entrained flow and cyclone type gasifiers. To create a stable process of gasification, Samy 2013[9] compressed the raw cotton gin waste using an auger and adding an external heater for gasification. Other researchers applied fluidisation of particles using a cyclonic method or other fluidised types of gasifier [6, 9, 27-30]. However, some feedstocks were found to face considerable difficulties in fluidisation. Because of the high mineral content of the non-woody biomass, the formation of low melting ash such as alkali silicates can create problems in fluidized bed reactors. The formation of a sticky glassy melt may cause bed particle agglomeration and this may lead to fluidization failure and operational shutdown [5].

For typical non-woody biomass which has density problems, a fixed bed is rarely directly used for raw feedstock. A fixed bed gasifier generally requires the ability of the feedstock to flow naturally, passing each zone of drying, pyrolysis, combustion and gasification. Each zone is naturally conditioned by the required amount of oxidant to fuel ratio. The low flow ability of raw low density feedstock may affect the space in the gasifier reactor to be occupied by air instead of the feedstock. This may create a fluctuating condition of air to fuel ratio so the expected zone conditions cannot be reached. Therefore, to be used in a fixed bed, the pre-treatment of densification is usually required. Jordan and Akay 2012[31] studied sugarcane bagasse pellets gasified in a downdraft type unit. The amount of tar was low due to pelleting the materials and the associated tar cracking in the pyrolysis bed zone in

the downdraft type as the gas exits. Nevertheless, without upgrading the fuel, the types of tar from sugarcane bagasse were easy to condense even at low concentration. These tars were formed at low temperatures of about 90°C. To reduce this effect, granular CaO were mixed with pellets to enhance the tar cracking capabilities [22].

4.2 *Upgrading pellet fuel through co-gasification*

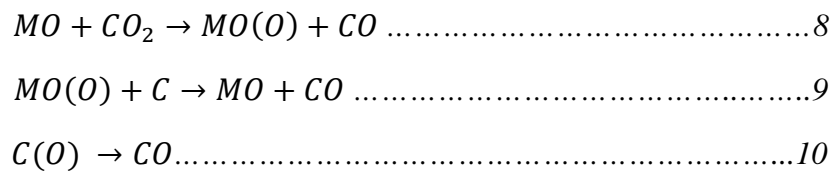
To overcome the problem of high ash and tar problems in gasification of non-woody pellets due to minerals present, the non-woody biomass can also be mixed with other selected materials. The mixture of non-woody biomass in gasification can be with a catalyst or other high grade fuel. The mixtures with commercial catalyst such as dolomite, NaOH, NaCl, CaO, ZnO, NiO have been investigated by Mohammed *et al.*, 2012[32] in order to reduce the tar problems and increase efficiency of syngas production.

Alternatively, this may be achieved by mixing the non-woody materials with other higher quality solid fuels. By mixing with the solid fuel, not only is the pellet fuel quality upgraded, but this also reduces various technical problems related to the gasification of non-woody biomass [33-42]. Research has shown that co-gasification has two “synergistic” beneficial effects namely tar cracking and catalytic gasification.

Currently, studies on biomass co-gasification are both for non-woody and woody materials. In most studies, the biomass was mixed with coal (Table 5). Biomass and coal (or charcoal in general) are quite different in terms of their relative chemical compositions. Biomass has higher volatile content whilst charcoal has more fixed carbon. Biomass gasification has the tendency to produce tars and high reactivity. Charcoal thermochemical conversion has a slower reaction rate than that of biomass. By co-gasification with charcoal, the increased heat from the char can crack the tars produced from biomass gasification, resulting in more combustible gases and less tar production [43].

Furthermore, mixing non-woody biomass with charcoal in a co-gasification system may give another additional advantage. The mineral content of alkali and alkali earth metal (AAEM) of the non-woody biomass, i.e. potassium, calcium, sodium and magnesium can act as a natural inexpensive catalyst during gasification [36]. The catalytic effect can increase char reactivity producing more combustible gases and increasing the efficiency compared to the individual gasification effect of each fuel [10]. The catalytic potential comes from alkali (K^+ , Na^+), alkaline earth (Ca^{2+} and Mg) and transition (Fe^{2+}) metals. The availability of AAEM catalyst (M) can increase the production of CO gas in syngas. The mechanism of

these catalyst (M) and CO₂ as reactant gases in catalytic gasification may be described in the reactions below [44]:



Studies on biomass catalytic gasification are summarised in Table 6. Based on these studies, catalytic gasification can be created by firstly adding the external mineral based catalysts into the biomass and secondly by natural catalytic activities from mixtures of biomass-charcoal in co-gasification. In the first case, a commercial catalyst can be added into the biomass to reduce the tar problem and increase biomass gasification efficiency. The catalyst addition together with appropriate gasification temperature can increase the shift reactions of the tars, such that the output of devolatilisation gas and tar cracking gas species (Eq 6 and 7) were increased [32, 45]. In the second case of the co-gasification of the biomass-charcoal, the increase of syngas conversion is expected from the synergistic occurrence. The catalysts are anticipated sourced from the mineral content inside of the biomass, while the heat is expected from the charcoal exerted from its slow thermal degradation characteristic. Dependent upon the natural process, the catalytic reactions from biomass-coal co-gasification can be achieved if such conditional factors for synergistic are fulfilled. However, the co-mixture biomass-charcoal may produce more potential carbon based gases (CO, CH₄, C_mH_n) sourced from the addition of carbon reactions of the charcoal.

Overall, the synergistic effects in co-gasification are still unclear. There are three groups of results related to the synergistic effects of co-gasification. The first found no synergistic effects. It showed similar syngas production results in co-gasification with the sum of each individual fuel separately gasified [35, 38, 46]. Nevertheless, they reported that adding the coal did effectively reduce tar production. The second group reported a negative synergy in which the results of co-gasification were even lower than the sum of individual gasification. They argued that the carbon in this case might produce carbonaceous gases (CO, CO₂, CH₄) [47]. The mineral inhibition might also diminish the work of catalytic gasification. The potassium catalyst was inhibited by the presence of Aluminium minerals at molar ratio (Molar K/Al) less than 1 [34]. The last group revealed synergistic effects in their results shown by higher char reactivity, higher conversion efficiency and/or the presence of

catalytic activity in co-gasification when compared to single fuel gasification [33, 36, 48-50]. Nevertheless, most of the researchers who found insignificant results of synergy agreed that co-gasification had reduced tar problems as the coal addition had stabilized the gasification temperature. This option of co-gasification may thus be a promising method to reduce the technical problems of non-woody biomass gasification. It was argued that insignificant results in synergistic occurrences may be due to factors such as the design of reactors, reaction temperature, appropriate mixture ratios and the sample size [10, 51-54].

4.3 *Factors influencing the effect of co-gasification*

In biomass co-gasification with charcoal, blending the biomass and charcoal is intended to reduce the deficiencies in each fuel. Biomass in general has high hydrogen (H) content. This can compensate the low H content of coal. On other hand, biomass which has high volatile and low gasification temperature will release more tar. Blending with coal may also reach higher gasification temperature than biomass alone gasification temperature. This will provide more heat to crack the tar [10].

As coal has higher carbon content, the gaseous products containing carbon content (CO₂, CO, CH₄ and other light hydrocarbons) should be higher in coal gasification compared to biomass gasification [24]. However, research has indicated that increasing the biomass could also increase the carbon content of gases [35, 36, 46]. Kumabe *et al.*, 2007[46] found that CO gas was independent to the effect of biomass increased, but the methane gas production was increased in co-gasification showing a synergistic reaction in comparison to each fuel gasification. There were some other factors influencing the increase of carbon content gaseous at the increase of biomass ratio to coal. In their experiments, Kumabe *et al.*, 2007[46] also further applied higher oxidant and lower temperature than that coal gasification. This resulted in more char reactivity producing more carbon based gaseous compared to coal gasification alone.

Hydrogen production in co-gasification cannot be predicted by only examining the influence of biomass composition in the mixture of biomass-coal. It will also be subject to the effect of gasification temperature and pressure. Many researches showed that the hydrogen was reduced with the increase of biomass [35, 46, 55]. Adding the biomass which has high volatile would reduce the gasification temperature leading to reduction of hydrogen. Lower temperature may induce more methanation reactions, consuming the available H₂ [56]. However, researchers found an increase of hydrogen as the increase of biomass in mixtures

[37, 57]. This could be reached by applying slightly high temperatures than biomass gasification temperature, reducing oxidant or applying adequate pressure.

The gas yield is defined as the production of combustible gaseous per weight of dry and ash free feedstock. Gas yield in co-gasification biomass-coal was reported to increase by the increase of biomass composition [46, 47, 50, 57]. They reported that due to high oxygen content in biomass and carbon content in coal, the CO production was increased. They also highlighted that with higher volatiles in biomass the methane gas was also increased.

In general, rising temperature will increase carbon conversion, total gas and lower tar. In steam gasification, increasing temperature will increase hydrogen and decrease CO₂ [49]. Increasing temperature will also reduce methane and hydrocarbon formation [47]. Nevertheless, a catalytic co-gasification observation found that increasing temperature would evaporate potassium in biomass. Thus this might cause insignificant synergy of co-pyrolysis product [34, 58]. On the other hand, low pyrolysis temperature also led to low concentration potassium available in the char for catalytic reaction. Zhu *et al.*, 2008[40] reported that potassium content in the co-pyrolysis chars was the highest in the pyrolysis temperature of 750°C compared to 650°C and 850°C. The synergistic effect did not occur in the co-pyrolysis. However, when applying further heat of 900°C mimicking the gasification temperature, it was found that the highest potassium char from pyrolysis of 750°C had also highest char reactivity in the gasification. This showed that although the synergistic effect in the pyrolysis stage might not be very clear, the optimum pyrolysis temperature could provide char with maximum content of catalyst. This might be useful for synergistic effect at the next stage of reduction reactions.

Given that gasification is a complex process, relevant factors are often interrelated. Therefore, the optimisation of the factors influencing the operations would need to consider specific feedstocks co-gasification in a particular gasifier type. The pre-treatment of feedstock may also influence the synergistic effect. Pelleting the mixture promotes a more uniform mixture of the fuels. It also promotes a uniform co-gasification allowing them for interacting with each other for co-gasification. Loose mixture may gasify separately due to density difference as they will segregate during feeding or in the process of gasification itself [59].

4.4 *Co-gasification of biomass and coal*

Co-gasification of biomass and coal has been studied for a medium to large scale gasifier plant of fluidized bed and entrained gasifier types [33, 35, 45, 47, 49]. A number of

researchers also conducted co-gasification trials in small scale fixed bed plants [37, 46]. For small to medium scale plants, a fixed bed may be more suitable and easy to control in contrast to the fluidised types. In terms of co-gasification, a fixed bed compared to a fluidised one may provide more intimate contact between neighbouring fuel particles, which may in turn provide better conditions for achieving synergistic effects. Sufficient residence time is also a factor influencing the possibility of synergistic effects. The process of gasification in downdraft types takes place at the reduction zone. The function of coal in this co-gasification is to create more stable temperatures in that zone; hence the slow process may crack the tars and promote more of the chars' reactivity. Collot *et al.*, 2009[38] studied the co-gasification in fluidised and fixed bed types. They did not find any synergy in fluidized reactors. However, they found a slight increase, although not significant, of tar cracking in the fixed bed.

A number of researchers studying co-gasification of biomass-coal used biomass as either the supplement for coal gasification [40] or vice versa, such that the coal was used as a supplement for biomass gasification [42]. It was found that using highly volatile coal (low to medium rank coals) co-gasification with biomass could result in higher gas conversion efficiencies when compared to the application of high rank coal [37, 42]. Though having higher energy content, applying high ranked coal resulted in more char residue instead of higher carbon conversion to combustible gases. This was because high ranked coal is more inert than lower ranks. Compared to low ranked coal, mineral components in high ranked coals had little catalytic activity during coal gasification [10]. In the high ranked coal, the calcium is typically in the form of calcite, decreasing the catalytic activity and the potassium present is transformed into potassium aluminosilicate glass. Thus, the natural mineral catalyst in co-gasification may be better sourced from biomass.

The utilization of the blended coal and biomass may lead to economically more flexible and reliable operation for an energy plant. However, the issue associated with the release of the mixed char should be treated carefully to avoid soil contamination. Another potential use is the mixing of biomass with bio-char. The bio-char may have characteristics close to coals in which it has high fixed carbon but could be slightly higher volatile than high rank coals, lower ash and sulphur content than low rank coals.

5 Future Direction of Non-Woody Gasification

As stated previously, there are two approaches in the utilization of the non-woody biomass for gasification. Firstly is the modification of the gasifier to suit with the non-woody

properties and secondly is the improvement of the quality of non-woody as solid fuel. To accelerate the commercial applications, in the near future, it might be better to first focus on the improvement of the quality of non-woody as solid fuel, so that it can be fed into the available gasifier or other existing thermochemical energy converters in general without much more modification. The best option to improve the quality of non-woody as solid fuel may be through upgrading it into good quality of pellet fuel. Research is being conducted investigating the influence of the different processing parameters on the properties of the formed pellets. The pre-treatment of pelleting consumes about 3.3 MJ/kg energy for its production. This is only about 15-20% of its energy content [73]. Furthermore, pelleting the waste can provide solid fuel feedstock that can be preserved for future use. This non-woody pellet may become an alternative of woody pellet that can be commercially available in the market.

The wood pellet has long existed in the market place, but it has just started to get significant market attention from year 2000s. It was reported that in the period 2006–2012, the wood pellet production in the world has been increased from 7 to reach 19 million tons [17]. Correspondingly, the ISO 17225 series: Solid biofuels-Fuel specifications and classes were also issued in the year of 2014. The release of this standard is timed to the anticipated increase in the market of solid biofuels utilization in the household and commercial area in which the application is more strict than in the industrial sector [60]. These standards are based on EU and USA standards where more mature market already exists in these regions.

Following the trend of wood pellet, the technology development of non-woody biomasses has also attracted considerable interest recently. For example, the part 6 of the ISO standard describes the grading of non-woody pellets. The inclusion of non-woody pellets in this standard has given an opportunity to non-woody pellets entering the market as an alternative to wood pellet.

For the majority of gasification processes used worldwide their current technologies are analyzed and optimized using experimental techniques in [24]. Although a variety of biomass gasification technologies have been proposed, very few are actually applied on a commercial scale. Many suppliers have developed pilot systems only, with a few manufacturers offering wood gasification models that have been tested in practice. Due largely to production and development cost concerns, it is also noted that the majority of low power reactors of up to several hundred kW are fixed-bed devices [24].

The syngas produced by gasification can be burnt directly or fuelled to a gas engine or gas turbine to provide any combination of heat, mechanical or electrical energy. The

development of gas generators, gas scrubbing systems and methods for managing process residues contributes to progress in biomass gasification technology [24]. The syngas production utilising waste from agricultural processing plant can be re-utilised to the plant as an alternative energy or providing self-sufficiency energy of the agricultural processing. At this time, some processing plants, e.g. sugarcane mills, oil palm mills, utilises their waste in a combustion system for fulfilling their energy needs. However, converting through gasification system may increase energy conversion efficiency. In solid fuel combustion, the average heat conversion efficiency can only approach some 20%, while the gasification heat conversion can reach about 30-70%, dependent upon the type of gasifier and the operation systems [61]. It is shown in Table 1 that the energy content of non-woody is approximately 16 MJ/kg, the potential syngas production is thus about 4.8-11 MJ/kg for non-woody materials. In Australia, from an average of 250,000 ha of cotton planting area each year, 0.1 million tonnes cotton gin trash may be available. This can potentially produce some 800,000 GJ of syngas per annum, if we assume a gasification conversion efficiency of 50%.

The gasification can also reduce pollutions. In solid fuel combustion, the fly ash should be treated carefully. This is in comparison with combusting the syngas which may be able to achieve lower air pollution. This could be important due to growing environmental concern. Furthermore, the gasification technology is also being used for producing hydrogen-rich syngas. Industrial gas to liquid conversion processes such as the Fischer-Tropsch process are being further developed to produce chemicals and fuels from biomass rather than traditional sources such as coal and natural gas [72].

6 Conclusion

Non-woody biomass is often categorised as a waste product. These residues may come from a range of industries, animal waste and herbaceous plants. In the cotton industry, for example, the CGT available for gasification in Australia alone amounts to around 0.1 million tonnes per year. This can potentially generate 800,000 GJ of syngas per year assuming a biomass conversion efficiency of 50%. 25 million tonnes and 5.6 million tonnes of straw and chaff are also produced every year from the wheat and barley farms in Australia respectively.

Currently, non-woody biomass is not efficiently utilized for energy conversion. The potential utilization of this type of biomass is promising, given that it is abundant and widely available. The energy conversion through gasification can achieve higher conversion efficiency and lower pollution compared to the combustion. However, it has been found that

low density, high silicate content characteristic of typical non-woody biomass can make this type of material relatively difficult to handle in the gasification process.

Efforts in the selection and improvement of gasifier design have been conducted to match with the nature of low density non-woody properties. However, some technical difficulties were still reported, such as fluidization problems or high input energy required for the operation. Therefore, upgrading the non-woody material into good quality of solid fuel may be the best alternative option for feeding into the gasifiers. It can also fit well with the simplest gasifier design of the fixed bed type.

The efforts to improve the density can be achieved through either torrefaction and/or briquetting/pelleting of the biomass. With the use of an appropriate binding agent and the addition of some catalytic or higher heating value materials in the pelleting process, the quality of fuel can be significantly improved. The process of pelleting biomass only consumes about 15-20% of energy content of the pellets and improves the system reliability and fuel quality.

Studies of biomass co-gasification have mostly been conducted by mixing biomass with coal. The heat from the coal can crack tars formed, whilst the mineral catalyst in the biomass can induce catalyst gasification. Overall, the synergistic aspect in co-gasification is however not sufficiently proven so it requires further validation on a broader scale and a wider range of feedstocks and ratios. Another potential use is the mixing of biomass with bio-char

In the future commercial applications of gasification, the quality of non-woody as a solid fuel will need to be improved. In a co-mixture and pelleted form, the properties of non-woody as a fuel can be upgraded into a good quality of solid fuel to achieve a more consistent gasification performance. In the form of pellet, controls are of a comparable level to that of a liquid/gas fuelled system and this will also promote automated operation. In the future, the gasification of densified non-woody waste solid pellets could well provide an attractive alternative fuel source to achieve both energy self-sufficiency and off-grid operation.

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Table 1 Proximate and ultimate analyses of feedstock

Feedstock	Proximate (% as received)				Ultimate (% ash free)					High Heating value (MJ/kg)	Density (kg/m ³)	Reference
	FC	VM	M	Ash	C	H	O	N	S			
<i>Non Woody</i>												
Cotton gin waste	20.8	68.7	11.8	10.5	45.14	4.93	40.43	1.16	0.29	16.6	390	Samy 2013[9]
Sugar cane bagasse	31	65	9.4	3.6	49.4	6.3	43.9	0.3	0.07	18.9	68	Jordan and Akay 2012[31]
Oil palm empty fruit bunch	8.79	82.58	5.18	3.45	46.62	6.45	45.66	1.21	0.035	17.02	1422	Mohammed <i>et al.</i> , 2012[32]
Switchgrass	16.8	76.9	6.0	6.3	47.9	6.2	45.0	0.8	0.1	19.6	115.4	Masnadi <i>et al.</i> , 2014[58] Mani <i>et al.</i> , 2006[62]
Beef cattle manure	11.15	59.05	13.08	29.8	35.4	5.04	27.58	1.79	0.4	15.93	NA	Maglinao Jr <i>et al.</i> , 2015[29]
Rice straw*	17.25	69.33	NA	13.42	41.78	4.63	36.57	0.7	0.08	16.28	75	Jenkins and Ebeling 1985[63]
Corncoobs*	18.54	80.10	NA	1.36	46.58	5.87	45.46	0.93	0.16	18.77	282	Jenkins and Ebeling 1985[63]
Rice hulls*	16.67	65.47	NA	17.86	40.96	4.3	35.86	0.4	0.02	16.14	70-145	Jenkins and Ebeling 1985[63]
<i>Woody</i>												
Sawdust*	16.27	82.45	NA	1.28	50.26	6.14	42.2	0.07	0.05	20.47	NA	Lapuerta <i>et al.</i> , 2008[36]
Macadamia shells*	23.68	75.92	NA	0.40	54.41	4.99	39.69	0.36	0.01	21.01	680	Jenkins and Ebeling 1985[63]
Coconut shells*	21.38	77.82	NA	0.8	49.62	7.31	42.75	0.22	0.10	20.8	NA	Iqbaldin <i>et al.</i> , 2013[64]
Redwood*	19.92	79.72	NA	0.36	50.64	5.98	42.88	0.05	0.03	20.72	481	Jenkins and Ebeling 1985[63]
<i>Coal (examples)</i>												
Lignite	27.8	24.9	36.9	10.4	71.0	4.3	23.2	1.1	0.4	26.7		Higman and van der Burgt 2008[65]
Sub-bituminous	43.6	34.7	10.5	11.2	76.4	5.6	14.9	1.7	1.4	31.8		
Bituminous	54.9	35.6	5.3	4.2	82.8	5.1	10.1	1.4	0.6	36.1		
Anthracite	81.8	7.7	4.5	6	91.8	3.6	2.5	1.4	0.7	36.2		
<i>Bio-char</i>												
Wood charcoal	67.5	18.7	6.1	7.7	77	4.2	11.5	0.3	0.6	30.3	NA	Rasul 2001[66]
Coconut shells charcoal*	76.32	10.6	NA	13.08	NA	NA	NA	NA	NA	30.75	NA	Mozammel <i>et al.</i> , 2002[67]

*Moisture free (dry fuel)

Table 2 Literatures on the biomass pellet

Material	Method	Analyses	Reference
Cotton gin by product	Treatments: - Addition corn starch 4% (gelatinized) & 10% '(5% gelatinized + 1% dry) - Addition 5% corn starch (4% gelatinized + 1% dry), & 5% cotton seed oil Machine: - Lab scale extruder for mixing and making slurry before entering commercial pellet mill - Water was added when entering pellet mill for moisture content of 15% -20%	<ul style="list-style-type: none"> • Bulk density (ASTME873) • Calorific value(D5865) • Ash(D1102) • Total sulphur(ASTMD4239) • Water soluble sodium(ASTME776) • Maximum pellet length (PFI) • Fines (PFI) • Proximate(Moisture, volatile, Fixed carbon) • Ultimate(C,H,N,O) 	Holt <i>et al.</i> , 2006[14]
Pruning residues of <i>Olea europaea L</i>	Using single pelleter. Treatments : 1. pressure 2000, 3000, 4000, 5000 N 2. Temp 60, 90,120, 150°C 3. Biomass Moisture content 5,10,15,20% (w.b.) 4. Particle size 1 mm, 2 mm, 4 mm	-Mass, dimensions & density - Durability: specific rigidity - Statistical analysis: The response of treatments to density and modulus elasticity	Carone <i>et al.</i> , 2011[68]
Wheat straw bonded with - wood residues - pre-treated wood residues - glycerol - lignosulfonate - Bentonite - wood residue with glycerol	Methods: 1. Binder treatment <ul style="list-style-type: none"> • Single pelleting • 0% binder • 2% Lignosulfonate • 2% bentonite • 5% glycerol • 10%,20%,30% wood residue • 10%,20% & 30% microwave pre-treated wood residue • 10%,20%,30% microwave pre-treated wood residue with glycerol 5% 2. 9.5%-10% Moisture 3. Particle size: mean geometric 0.858 mm 4. Compressive press 4000 N, stop 60 second	<ul style="list-style-type: none"> • Pellet density, dimension and relaxed density (14 days) • Specific energy consumption • Tensile strength • Higher heating value • Statistical analysis of the effect of binders on the physico-chemical characteristics 	Lu <i>et al.</i> , 2014[18]
Grasses (Wheat & barley straws, corn stover, switch grass)	Method: 1. Ground at screen size 3.2, 1.6, 0.6 mm) 2. MC at 12% & 15% 3. Compression/pelleting using single pelleter unit 4. The die heated up to 100°C 5. The loads were 1000, 2000, 3000, 4000 and 4400 N, held for 60 s. 6. Repeated 5 times	<ul style="list-style-type: none"> • Statistical analysis of the applied forces on pellet density (Duncan multiple range tests) • Analysis residual modulus after relaxation • Analysis chemical composition: Protein, crude fat, lignin, cellulose, hemicellulose, ash 	Mani <i>et al.</i> , 2006[62]

Table 3 Gasifier Types [69]

	Fixed bed		Fluidised bed		Entrained flow
	Downdraft	Updraft	Bubbling bed	Circulating fluidised	
Suitable scale (MW)	<5	< 20	10-100	20-100	>100
Tars	Low	High	Medium	Medium	Very low
Gasification temperature (°C)	700-1200	700-900	< 900	1450	1450
Control	Easy	Very Easy	Moderate	Moderate	Hard
Feedstock preparation	Very critical	Critical	Less Critical	Less Critical	Only fine particles

Table 4 Non-woody biomass gasification

Materials	Type of gasifier	Reference
Sugarcane bagasse	Cyclone gasifier	Gabra <i>et al.</i> , 2001[30]
Oil palm empty fruit bunch	Bubbling fluidized bed	Lahijani and Zainal 2011[6]
Sugar cane bagasse pellet, Oil palm empty fruit bunch pellet, Wood pellet	Downdraft gasifier	Erlich and Fransson 2011[70]
Cotton gin waste	Fluidized bed gasifier	Groves <i>et al.</i> , 1979[71]
Cane bagasse pellet	Downdraft gasifier	Jordan and Akay 2012[31]
Sugar cane bagasse	Fluidized bed gasifier	Sahoo and Ram 2015[27]
High tonnage sorghum, cotton gin trash, beef cattle manure	Fluidized bed gasifier	Maglinao Jr <i>et al.</i> , 2015[29]
Raw cotton gin waste, torrefied cotton gin waste	Auger system gasifier	Samy 2013[9]

Table 5 Biomass co-gasification

Materials	Type of gasifier	Reference
Silver birch wood & coal	Fixed bed and fluidised bed	Collot <i>et al.</i> , 2009[38]
Japanese cedar, rice straw, seaweed with low rank coal	Downdraft gasifier (air and steam as oxidant)	Rizkiana <i>et al.</i> , 2014[37]
Pine pellet and petroleum coke	Bubbling Fluidised bed	Nemanova <i>et al.</i> , 2014[42]
Olive bagasse & coal	Fluidised bed type	André <i>et al.</i> , 2005[72]
Forestry waste (pinus pinaster pruning), agricultural waste (grape & olive pruning), Industrial waste (sawdust & marc of grape) with coal-coke	Circulating flow gasifier	Lapuerta <i>et al.</i> , 2008[73]
Pine chips mixed with black coal, low grade coal & Sabero (refuse coal)	Fluidised bed (mixtures of air and steam as oxidant)	Pan <i>et al.</i> , 2000[74]
The pellet of mixtures lignite and <i>Eucalyptus nitens</i> wood	Fluidised bed types (bubbling fluidised bed and dual fluidised bed) with steam as oxidant	Xu 2013[33]
Woody biomass (Japanese Cedar) & Brown coal (Mulia coal)	Downdraft (air and steam as oxidant)	Kumabe <i>et al.</i> , 2007[46]

Coal, pine and Polyethylene waste	Fluidised bed type (air and steam as oxidant)	Pinto <i>et al.</i> , 2003[47]
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Table 6 Studies on catalytic activities in gasification

Materials	Catalysts	Remarks	Reference
Empty fruit bunch oil palm (EFB)	Malaysian dolomite (P1) Malaysian dolomite (GML) NaOH NaCl CaO ZnO NiO	Adding dolomite at gasification temperature of 850°C significantly increased the H ₂ in Syngas composition. The catalytic reactions enhanced more occurrences of water shift reactions.	Mohammed <i>et al.</i> , 2012[32]
Cane bagasse pellet fuel	Granular CaO was mixed with pellet fuel.	The mixture of up to 6% granular CaO with the cane bagasse pellet fuel was fed into a downdraft gasifier bed. The tar content in syngas was reduced up to 80% and the syngas yield was increase 17-37%.	Jordan and Akay 2013[22]
Illionis 6 coal and switchgrass co-gasification	Switchgrass as source of potassium catalyst	Both switchgrass char and ash displayed catalytic activity in mixture with coal. At mixture ratio of 1:9 of coal: switchgrass ash and temperature at 895°C, gasification rate reached eight folds.	Brown <i>et al.</i> , 2000[75]
Meat and bone meal (MBM) char and coal (anthracite and lignin) co-gasification	Natural catalyst (Sodium and Calcium) from MBM	The co-gasification rate of anthracite-MBM at 950°C was 1.5 faster than individual materials.	Ren <i>et al.</i> , 2011[76]
Biomass (Sawdust and Switchgrass) and coal (sub-bituminous and fluid coke) co-gasification	Natural catalyst of potassium from the biomass	Potassium and aluminosilicates molar composition in the mixture had effect in the inhibition and catalytic activities in co-gasification.	Masnadi <i>et al.</i> , 2015[77]