Characterization of Coconut (*Cocos nucifera*) Husk and Shell for Gasification: A Study on Fouling and Slagging Tendencies

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ABSTRACT

The melting of the feedstock's inorganic components under gasification temperatures and its subsequent deposition in the heated surfaces of a gasifier causes inefficiencies and operational problems. The study evaluated the compatibility of coconut husk (c-husk) and coconut shell (c-shell) for gasification based on biomass characterization, prediction of fouling and slagging tendencies, and determination of the ash melting point. ASTM standards were used to characterize both biomass where c-shell is found to be an appropriate feedstock for gasification because of its high volatile matter (83.5%) and bulk density (702.1 kg-m^3). Slagging and fouling tendencies during thermal conversion were determined using empirical indices such as Alkali index (AI), base-to-acid ratio ($R_{b/a}$) and bed agglomeration index (BAI). Results revealed that all indices predict c-shell will not exhibit slagging and fouling but c-husk will. Moreover, slagging (R_s) and fouling (R_f) factors, which are commonly used for coals, were also used and projected that c-shell has low-slagging and medium-fouling potential while c-husk has severe-slagging and fouling potential. Furthermore, the compressive strengths of c-husk and c-shell ash pellets treated at gasification temperatures were measured to indirectly determine the temperature at which slagging and fouling is likely to occur. The ash melting temperature were determined to be less than 600°C for c-husk and greater than 900°C for c-shell. Hence, ash melting problems are expected only in c-husk gasification. C-shell, on the other hand, is found to be a suitable feedstock at typical gasification temperatures.

Keywords: ash melting temperature, coconut husk, coconut shell, gasification, fouling and slagging indices

INTRODUCTION

Cocos nucifera trees, commonly known as coconut palm trees, can be found in tropical and subtropical countries. It has been regarded as the "tree of life" because it can provide the basic necessities of life like food, drink, oil, medicine, fiber, timber, and fuel (Chan and Elevitch, 2006). In the Philippines, the industry of coconut farming has approximately 500 million trees which are the largest number in the world (Zafar, 2014). Consequently, billions of coconuts are expected annually in the country, considering that an average coconut tree produces approximately 120 nuts per year (Bradley *et al*., 2006). However, large production of coconuts also come with biomass waste residues. Annually, coconut farms generate about 10.4 million tons residues which can be explored as a potential renewable source for energy conversion (Zafar, 2014).

Research on biofuels has been a field of interest for many experts because of its abundance and carbon neutrality characteristics. Thermochemical conversion processes are commonly used to extract biofuel from lignocellulosic biomass like coconuts. Heat and pressure are applied during thermal conversion to break down the biomass and produce biofuels. Such processes involve torrefaction for biochar production, pyrolysis for bio-oil, gasification for synthesis gas, and combustion for heat generation. Gasification, among others, has been determined to have the highest efficiency (Sharma and Sheth, 2016).

In a gasification process, biomass is subjected to an oxygen-starved environment with an elevated temperature (300-1200°C). The desired product produced in the process is the synthesis gas or "syngas" which is dominantly composed of carbon monoxide and hydrogen. The equipment used to perform gasification are called gasifiers, which are generally classified into three depending on the entry point of the oxidizing agent and the exit point of the syngas. This involves upward draft (counter-current), downward draft (co-current), and cross-draft gasifier (Capareda, 2014).

Energy conversion studies on coconuts are mostly focused on the shell, husk, and oil from coconut meat (Sulaiman *et al.*, 2010, Banzon, 1980, Wan Ab Karim Ghani *et al.*, 2009). Specifically, Wan Ab Karim Ghani *et al.* (2009) had studied the effects of operating temperature, fluidization ratio, static bed height, and equivalence ratio on the syngas quality when coconut shell was subjected to air-gasification. The quality of the syngas is also significantly affected by the oxidizing medium which could be air, steam and oxygen. Although the use of coconut residues as a feedstock for gasification has already been explored, there are still limited literatures which evaluated its suitability to gasification in terms of fouling, slagging and bed agglomeration tendencies. These elements for suitability evaluation are significant to avoid severe gasifier malfunction and serious maintenance (US Department of Energy, 2013).

When exposed to high-temperature treatments like gasification, the inorganic components (ash) of biomass may undergo melting that eventually leads to fouling, slagging, and bed agglomeration. According to Teixeira *et al.* (2012), slagging is the deposition of molten ash to high-temperature refractory sections of reactors where radiative heat transfer is principal; while fouling is a deposition that takes place in the convective heat transfer zones where gases start to cool down. On the other hand, bed agglomeration only happens in fluidized bed gasifiers (FBG) where melted ash sticks to the bed materials and acts as an adhesive that leads to the formation of bed aggregates. The melting of ash and its deposition, which narrows down the heated components of gasifiers, has been considered as one of the biggest problems of thermal conversion industry (Tortosa-Masia *et al*., 2005). It has an implication on heat transfer rates which decreases the system's efficiency. Moreover, the accumulation of deposits may give rise to mechanical damages that can cause a facility shut down for maintenance. Despite the impacts of fouling and slagging phenomenon in the thermal conversion of biomass wastes, there are still few studies conducted to address these problems.

OBJECTIVES

The general objective of the study was to evaluate coconut residues, such as the husk and shell, for its suitability as a feedstock for gasification.

Specifically, the study aimed to characterize the mentioned coconut residues in terms of proximate, ultimate and physical properties; to estimate the slagging and fouling tendencies using empirical indices; and lastly, to determine the ash melting temperature.

METHODOLOGY

Materials

The c-husk and c-shell used in the study came from a coconut farm in Nagcarlan, Laguna, Philippines. These residues were extracted from mature or "brown" coconuts. The c-husks were directly sourced from the coconut farm whereas the coconut shells were collected from a local market stall which sells coconut milk.

According to Tooy *et al*. (2014), the water content of coconut husks at harvest is about 29-35%. The c-husks used in the study were already extracted from the coconut before these residues were delivered to the researchers. Moreover, the date of husk extraction and its period of exposure to the atmosphere were not identified. However, its as-received moisture content was determined low enough. Hence, c-husks were not subjected to drying.

The c-shells, on the other hand, were immediately acquired from the market. The c-shells were subjected to sun-drying to avoid fungal formation in the coconut meat residues. The resulting dried coconut meat residues were then removed from the c-shells. Both c-husks and c-shells underwent size reduction using hammer mills with 1 mm and 2 mm sieve size, respectively.

Location of the Study

The study was conducted at Texas A&M University (TAMU) using biomass materials from the Philippines. The shipment of plant-based material to the USA followed a quarantine requirement by the Bureau of Plant Industry where both biomass had undergone fumigation and phytosanitary procedure. However, the effects of exposing c-husk and c-shell to methyl bromide for 24 hours were not evaluated in the results of the study.

Characterization of c-husk and c-shell

ASTM standards were followed in characterizing c-husk and c-shell. Proximate analysis was done according to ASTM 872-82 (Standard Test Method for Volatile Matter in the Analysis of Particulate Wood Fuels) for the volatile combustible matter, ASTM E1755 (Standard Test Method for Ash in Biomass) for ash, and the fixed carbon content was computed by the difference. For ultimate analysis, the carbon, hydrogen, nitrogen, and sulfur components of the biomass were determined using ASTM E 777-08 for carbon and hydrogen, ASTM E 775-87 (2008) e1 for sulfur, and ASTM E 778-08 for nitrogen. Percent oxygen was determined by difference.

The higher heating value (HHV) was determined according to ASTM D5865 (Standard Test Method for Gross Calorific Values of Coal and Coke) using Parr isoperibol bomb calorimeter (Model 6200, Parr Instrument Company, Moline, IL). ASTM E871 (Standard Method for Moisture Analysis of Particulate Wood Fuels) was used for moisture content determination. Bulk density was determined following ASTM E873-83 (Standard Test Method for Bulk Density of Densified Particulate Biomass Fuels), while the particle density was characterized using an Accupyc 1330 pycnometer (Micrometritics).

Ash analysis of c-husk and c-shell

Raw c-husk and c-shell were placed in Thermolyne Muffle Furnace, set at 575°C, to extract the ash components. The collected ashes were sieved using mesh 140 to homogenize the particle size. Ash samples were sent to Huffman Laboratories (Denver, Colorado) for metal oxide determination. This test followed ASTM D6349 (Standard Test Method for Determination of Major and Minor Elements in Coal, Coke, and Solid Residues from Combustion of Coal and Coke by Inductively Coupled Plasma—Atomic Emission Spectrometry). The metal oxides, that were determined, are Al_2O_3, CaO, Fe_2O_3, MgO, K_2O, SiO_2, Na_2O, SO_3 and TiO_2.

Slagging and Fouling Indices

Using the values of metal oxides, empirical indices such as alkali index (AI), the base-to-acid ratio (Rb/a) and the bed agglomeration index (BAI) were calculated. These indices were used to evaluate the fouling and slagging tendency of c-husk and c-shell when exposed to gasification temperatures. Equations 1, 2 and 3 were used to calculate the three empirical indices. Equations 4 and 5, on the other hand, were used to compute for slagging factor (R_s) and fouling factor (R_f), respectively. The calculated R_s and R_f were compared to the slagging and fouling index used for coals to determine the degree of tendency (low, medium, high, and severe) that the coconut shell and husk ashes might exhibit.

$$AI = \frac{kg(K_2O + Na_2O)}{GJ} \quad \text{Equation 1}$$

$$R_{b/a} = \frac{\%(Fe_2O_3 + CaO + MgO + K_2O + Na_2O)}{\%(SiO_2 + TiO_2 + Al_2O_3)} \quad \text{Equation 2}$$

$$BAI = \frac{\%(Fe_2O_3)}{\%(K_2O + Na_2O)} \quad \text{Equation 3}$$

$$R_s = R_{b/a} \times S \quad \text{Equation 4}$$

$$R_f = R_{b/a} \times Na_2O \quad \text{Equation 5}$$

Ash Melting Point Determination

The melting or sintering temperature of ash is commonly attributed to the initiation of ash particle agglomeration -- a mass transport in between ash particles caused by heat. At temperatures below the ash melting point, the compressive strength of ash particles is strengthened partially due to inter-particle material bonds, filling the void fraction. But when exposed to its melting temperature, the particles tend to agglomerate which then reduces its surface energy (Schimpke *et al*., 2017). Stanzl-Tschegg (2009) further explained that when ash undergoes melting, its components crystallize which results to weaker compressive strength. With this, correlating the compressive strength of ash pellets as an indicator of melting temperature is widely accepted as reliable. Similar experiments were carried out by LePori (1986), Maglinao and Capareda (2010), Hupa *et al*. (1989), Nel *et al*. (2011), and Al-Otoom *et al*. (2000).

Ash samples were pelleted by applying a uniform load using a material stress test system (MTS model 810, Gray Machinery Co., Prospect Heights, III.). The dimensions of the pellets were kept at 12 mm diameter by 6 mm height for c-shell ash while 12.7mm diameter by 14mm height for c-husk ash. The size was carefully maintained for all the pellets by filling 10 grams of ash sample per pellet on a fabricated mold. The ash pellets were all subjected to heated air using a Barnstead Thermolyne 1400 Furnace set at 600°C, 700°C, 800°C, and 900°C. For each temperature setting, three ash pellets were heated for four hours. After cooling in a desiccator, the compressive strengths of each ash pellet were determined using the same material stress test system. A graph showing the relationship between temperature treatments and the resulting compressive strengths of pellets was generated from the results. The temperature at which the peak compressive strengths were observed was considered as the ash melting point of the biomass.

RESULTS AND DISCUSSION

Characterization of c-husk and c-shell

The results of the characterization of c-husk and c-shell are presented in Table 1. The table shows the proximate and ultimate analysis, moisture content, High Heating Value (HHV), and physical properties like the bulk and particle densities.

Not all biomass can be readily converted through gasification. The physicochemical properties of the feedstock have significant effects on the gasification products. Generally, most biomass with 15-30% moisture content can be used for gasification (Kirubakaran *et al*., 2009). Higher moisture content decreases the reaction temperature in gasification which leads to low-quality syngas. Results revealed that c-husk has an as-received moisture content of 7.06% while c-shell has 6.94%. With this, both biomass can be readily gasified considering their low moisture contents.

The proximate analysis determines the behavior of biomass when used as feedstock. It describes the composition of biomass in terms of volatile combustible matter (VCM), ash, and fixed carbon

Table 1. Characterization results of coconut husk and shell.

PROPERTIES	COCONUT HUSK	COCONUT SHELL
Proximate analysis $_{dry\ basis}$, $\%_{wt}$		
VCM[a], %	78.24	83.50
Ash[a], %	2.69	0.95
FC[b], %	19.07	15.55
Ultimate analysis $_{dry\ basis}$, $\%_{wt}$		
C	45.27	39.80
H	4.96	4.74
O[b]	46.43	54.42
N	0.62	0.08
S	0.03	0.01
Moisture Content[a] $_{as\ received}$, $\%_{wt}$	7.06	6.94
HHV[a], MJ/kg	17.62	18.68
Bulk density[a], kg/m^3	75.57	702.1
Particle density[a], kg/m^3	760	728

[a] analyzed in replicates n = 3
[b] analyzed by the difference

(FC). In gasification, volatiles are critical as they constitute most of the syngas components. According to Gaqa *et al*. (2014), gasification starts with an endothermic process that produces heat to release the moisture and volatiles from the feedstock. Volatiles are a mixture of short and long chain hydrocarbons which are thermally broken to lighter gases. Thunman *et al*. (2001) identified that volatiles are mainly composed CO, CO_2, H_2, H_2O, long hydrocarbon chains like tars (C_6H_6), and light hydrocarbons (CH_4). The left over carbon in the form of char reacts with air/oxygen and steam to produce more CO, CO_2, and H_2. Hence, biomass with high %VCM is more compatible with the energy conversion process focusing on gaseous fuels like gasification. Results showed that both the c-husk and c-shell have a relatively high volatile matter of 78.24% and 83.5%, respectively. From this, more syngas is expected from c-shell gasification because of its higher %VCM than c-husk. Moreover, the use of high %VCM feedstock for energy conversion reduces the risk of producing pollutants especially NO_x emissions. Pisupati (n.d.) reported that coals with higher VCM are generally associated with low NO_x emissions.

Another component determined in the proximate analysis is the ash content of the biomass, Rajvanshi (1986) reported that biomass with ash content lower than 5-6%, in general, have been observed to exhibit neither slagging nor fouling behavior. Hence, the low ash content of c-husk (2.69%) and c-shell (0.95%) infers that both have minimal tendency to slagging and fouling problems.

Lastly, the fixed carbon (FC) content tells the amount of residual solid carbon in the biomass after exposure to heat for a period of time. Higher FC was observed in c-husk (19.07%) than c-shell (15.55%). This result was expected because the ultimate analysis determined that c-husk has higher carbon content (45.27%) than c-shell (39.80%). Making charcoals or briquettes out of the biomass is a conversion process where FC content is critical. Torrefaction is a recommended treatment if char products are preferred. It is a process where feedstock is subjected to temperatures up to 220°C while being contained in a tightly-sealed reactor.

The ultimate analysis determines the percentage by weight of carbon (C), hydrogen (H), oxygen (O), nitrogen (N) and sulfur (S) of the biomass. Results can be used in setting up the empirical formula of the biomass and their complete combustion equations as shown in equation 6 for c-husk and equation 7 for c-shell.

$$C_{0.4527}H_{0.0496}O_{0.4643}N_{0.0062}S_{0.00003} + 0.4651(O_2 + 3.76\ N_2) = 0.4527CO_2 + 0.0248H_2O + 3.5N + 0.00003S$$

Equation 6

$$C_{0.2899}H_{0.4118}O_{0.2977}N_{0.0005}S_{0.00004} + 0.24(O_2 + 3.76\ N_2) = 0.29CO_2 + 0.21H_2O + 1.84N + 0.00004S$$

Equation 7

Bulk density is one of the important factors in evaluating the suitability of biomass for gasification. It has a considerable impact on storage and transportation costs. This property also affects the energy conversion efficiency in gasification. Biomass particles that are light enough can be easily flushed out with the syngas flow, thereby reducing its residence time inside the reactor which results to incomplete gasification (Jarungthammachote S., *et al.*, n.d.). Moreover, low-density biomass can easily result in bridging in continuous feeding-type FBG.

A bridge or a tunnel of biomass forms at the bottom of hopper bordering the diameter of the auger. Formation of the bridge means that even if the auger shaft continues to rotate, the biomass will not make contact with the auger. Hence, entry of biomass to the reactor is hindered. A shaking or stirring mechanism must be incorporated in the hopper design to avoid bridging. Another measure is to apply a pre-processing treatment like pelleting to increase the energy density of the biomass before using as a feedstock.

The study determined that c-husk has a low bulk density of 75.57 kg/m^3; a value comparable to most agricultural residues (20-200 kg/m^3). On the other hand, c-shell has a much higher bulk density of 702.1 kg/m^3 which belongs to solid woods (600-900 kg/m^3), as reported by Quaak *et al.* (1999). Based only on bulk density, c-shell is a more compatible feedstock for gasification because c-husk have a higher risk for bridging and low energy conversion due to its very low bulk density.

The particle density accounts only the solid component of the biomass. It represents the ratio of the weight of solids to its volume. Results revealed that c-shell has 728 kg/m^3 which is slightly higher than its bulk density. Particle density is always higher than bulk density because it does not account for the inter-particle voids that are filled up by air. For c-husk, a particle density of 760 kg/m^3 was measured which was much higher than its bulk density. This implies that in a given volume of c-husk, a large portion is taken only by air voids. Therefore, compacting or pelleting process must be taken into consideration during storage, shipment, and when used as feedstock.

Ash Analysis of c-husk and c-shell

Ash Metal Oxides Determination

Rajvanshi (1986) analyzed that the degree of the slagging and fouling behavior of biomass is based on their percent ash composition. Biomass with more than 12% ash is expected to exhibit severe slagging. Those with 6-12% ash content have slagging behavior that is highly dependent on the ash composition whether it will lead to low melting point mixtures. Biomass with below 5-6% ash content is known, in general, to be free from slagging problems. Knowing that c-husk and c-shell have 2.69% and 0.95% ash composition only, respectively, both biomass is expected to have a low inclination to slagging and fouling.

According to Vamvuka and Sografos (2004), alkali metals such as potassium (K), sodium (Na), and alkaline earth metals like calcium (Ca), magnesium (Mg), silicon (Si), chlorine (Cl), and sulfur (S) were identified as ash-forming elements. The metal oxides composition of c-husk and c-shell ash samples were determined in this study. Table 2 shows the results from which the slagging and fouling empirical indices and factors were computed.

As shown in Table 2, 80.46 % of c-shell ash is composed of silicon dioxide (SiO_2) while potassium oxide (K_2O) is the dominant component of c-husk ash, with 72.62%. According to Miles *et al.* (1995), the high concentration of silica in ash is advantageous because silica melts at 1700°C which is higher than usual gasification temperatures. On the other hand, potassium is associated with the

Table 2. Metal oxides composition of coconut husk and coconut shell ash.

METAL OXIDES	COCONUT HUSK		COCONUT SHELL	
	Amount per gram of ash, µg/g	Distribution, %wt	Amount per gram of ash, µg/g	Distribution, %wt
Al_2O_3	4,860	0.96	26200	5.40
CaO	24,600	4.88	12400	2.56
Fe_2O_3	13,100	2.60	23300	4.80
MgO	171	0.03	465	0.10
K_2O	366,400	72.62	23300	4.80
SiO_2	65,200	12.92	390300	80.46
Na_2O	29,900	5.93	6880	1.42
TiO_2	295	0.06	2230	0.46

formation of low melting point compounds. Potassium is an important factor in ash fusion and deposition especially when it combines with sulfur, chlorine, and silica. Therefore, based on SiO_2 and K_2O only, c-shell is expected to have a high melting point while c-husk is more prone to slagging and fouling because of its expected low melting point.

Prediction of Slagging and Fouling Tendencies

To predict whether a certain biomass will exhibit slagging and fouling when combusted, indices such as the alkali index (AI), the base-to-acid ratio (Rb/a), bed agglomeration index (BAI), Slagging factor (R_s), and Fouling factor (R_f) were used in this study. These indices were calculated based on the metal oxides composition of c-husk and c-shell ash, as shown in Table 3.

AI is the ratio of alkali oxide contents (K_2O and Na_2O) to the fuel energy (kg alkali GJ-1). According to Vamvuka and Zografos (2004), fouling or slagging will surely occur at AI above 0.34 kg GJ^{-1}. On the other hand, Munir (2010) stated that acidic compounds such as Al_2O_3, SiO_2, and TiO_2 improve the melting point of ash while basic compounds such as CaO, Fe_2O_3, MgO, K_2O, and Na_2O do the opposite. Hence, the basic to acidic compounds ratio ($R_{b/a}$) can be an index to predict ash deposit behavior. It has a positive correlation where, as $R_{b/a}$ increases, the slagging and fouling potential also increases. Results revealed that the high values of AI and $R_{b/a}$ for c-husk indicated that fouling and slagging is certain to occur during gasification. C-shell, in contrast, is safe from fouling and slagging problems.

Another index is BAI, which refers to the formation of bed particles into aggregates. In FBG systems, bed materials are used as a fluidizing medium where feedstock is introduced and uniformly burned. When ash components exhibit melting, it may not only stick on the heated components of the gasifier but also on the bed materials. The melted ash acts as an adhesive between bed particles which results in bigger particle sizes. Severe agglomeration leads to defluidization and can cause inefficiencies. Therefore, BAI is critical in FBG systems. In this study, a BAI less than 0.15 means that bed agglomeration will occur. Results showed that c-husk when combusted, will cause bed agglomeration while c-shell will not.

Slagging factor (R_s) and fouling factor (R_f), commonly used for evaluating coals (ASME, 1974), evaluates the severity of the slagging and fouling tendency. Both indices are based on the basic to acidic compounds ratio of the ash. R_s considers sulfur content that is related to the formation of alkali sulfates when reacted with potassium and calcium. Sulfates are known to be unstable at combustion temperatures. Presence of SiO_2 limits the formation of sulfates such as K_2SO_4 and $CaSO_4$, thus reducing the slagging tendency. On the other

Table 3. Fouling and slagging potential of c-husk and c-shell.

INDEX	TENDENCIES	COCONUT HUSK		COCONUT SHELL	
		Value	Remarks	Value	Remarks
Alkali Index, AI	<0.34, fouling or slagging will not occur	2.27	fouling and slagging will occur	0.04	fouling and slagging will not occur
Base-to-acid ratio, $R_{b/a}$	>1, fouling or slagging tendency increases	6.17	fouling or slagging tendency increases	0.16	fouling or slagging tendency decreases
Bed agglomeration index, BAI	>0.15, bed agglomeration will not occur	0.03	bed agglomeration will occur	0.77	bed agglomeration will not occur
Slagging factor, R_s	refer to Table 4	2.72	severe slagging potential	0.03	Low slagging potential
Fouling factor, R_f	refer to Table 4	36.57	severe fouling potential	0.22	medium fouling potential

hand, R_f considers sodium in the form of Na_2O. Sodium and potassium are present in organic biomass which tends to decompose and form eutectic compounds when exposed to high temperatures. These compounds have low melting points which cause slagging and fouling (Tortosa-Masia *et al.*, 2005 and Miles *et al.*, 1996).

Table 4 was used to describe the degree of fouling and slagging of c-husk and c-shell. Results revealed that based on R_s and R_f, c-shell has low-slagging and medium-fouling potential. Both factors have similar results with AI, $R_{b/a}$, and BAI that c-shell has a minimum tendency for fouling and slagging. C-husk, however, has R_s and R_f results which indicate severe slagging and fouling potential. Moreover, other indices such as AI, $R_{b/a}$, and BAI consistently predicted that c-husk has high tendency to slagging and fouling when subjected to high-temperature treatments.

Table 4. Slagging and fouling characterization used for coals.

SLAGGING/ FOULING TYPE	SLAGGING FACTOR, R_s	FOULING FACTOR, R_f
Low	< 0.6	< 0.2
Medium	0.6 to 2.0	0.2 to 0.5
High	2.0 to 2.6	0.5 to 1.0
Severe	> 2.6	> 1.0

Source: Maglinao and Capareda (2010)

Ash Melting Point Determination

To determine the temperature where ash will start to melt, c-husk and c-shell ashes were pelleted and exposed to typical gasification temperatures of 600°C, 700°C, 800°C and 900°C. The melting point was determined indirectly by measuring the compressive strengths of ash pellets after exposing to high temperatures.

In theory, the compressive strength of ash pellets will increase as the temperature treatment increases but only up to a certain degree. Once the inorganics have melted and made the pellets brittle, its compressive strength will immediately decrease. The temperature at which the compressive strengths of ash pellets have peaked was considered as the melting point. Ash melting point is a critical information because it represents the temperature limitation of biomass to avoid the occurrence of slagging and fouling. The compressive strengths of c-husk and c-shell ash pellets with respect to temperature are shown in Figure 1.

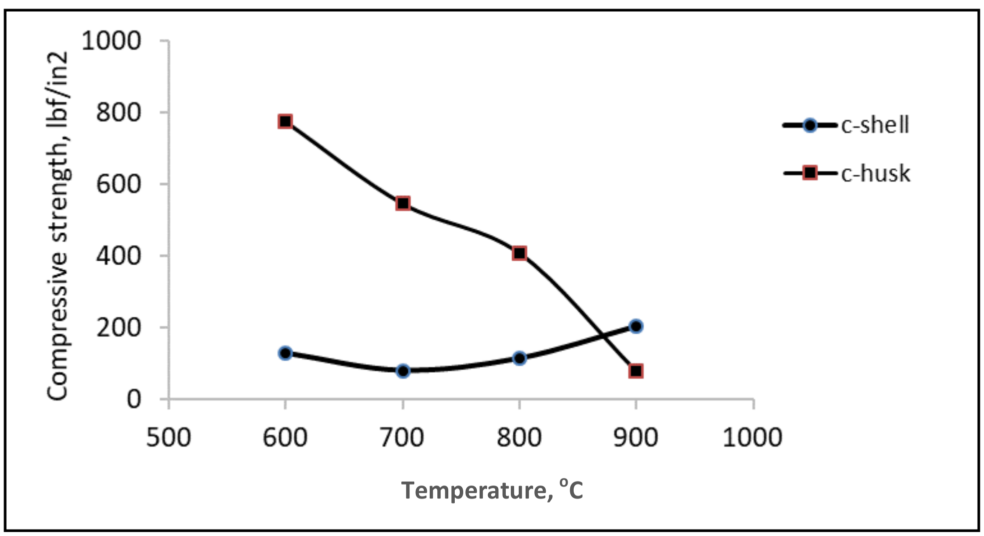

Figure 1. Compressive strength curve of c-husk and c-shell ash pellets heated at varying temperatures.

The temperature exposure was determined to have a significant effect on the compressive strength of ash pellets with a p-value of 3.14 x 10^{-7} for c-husk and 8.63 x 10^{-5} for c-shell. As shown in Figure 1, the compressive strengths of c-husk ash pellets have a decreasing trend with increasing temperature. It can be inferred that at temperatures above 600°C, the melting and crystallization of ash intensified which led to decreasing compressive strengths. The peak compressive strength of c-husk ash pellets was not determined from the set of gasification temperatures. Nevertheless, 600°C showed the highest compressive strength. Hence, the melting point of c-husk can be any temperature lower than 600°C which is not ideal for gasification to produce quality syngas.

As for the compressive strengths of c-shell ash pellets, a generally increasing trend was observed with increasing temperature exposure. The relatively high compressive strength at 600°C might be due to handling factors. The peak compressive strength was also not identified from the temperatures where c-shell ash pellets were exposed. However, the increasing compressive strength implies that there was only a gradual ash crystallization. Therefore, the ash melting point of c-shell may be at 900°C or higher.

CONCLUSION

In this study, the suitability of coconut husk and shell as feedstock for gasification was evaluated in terms of raw biomass characterization, prediction of slagging and fouling tendencies, and determination of ash melting point.

The proximate analysis determined that the high FC of c-husk makes it more preferable for char production (torrefaction) while the relative high % VCM of c-shell is suitable for syngas production (gasification). For continuous-feeding type FBG systems, the use of c-husk has a risk of bridging because of its low bulk density.

Metal oxides composition of c-husk and c-shell ash were determined to calculate AI, $R_{b/a}$, BAI, R_s, and R_f. These indices were used to evaluate the slagging and fouling tendencies of c-husk and c-shell during thermal conversion. AI and $R_{b/a}$ indices predicted that fouling and slagging are likely to occur in c-husk but not in c-shell. BAI further supported that melting and bed agglomeration will only occur in c-husk. The high K_2O of c-husk and high Si_2O of c-shell were the dominant reasons for such results. Additional indices commonly used for coals such as R_s and R_f were also used. As such, the calculated slagging and fouling factor garnered similar predictions where c-husk has severe slagging and fouling tendency while c-shell has low-slagging and medium-fouling potential.

Compressive strength was used to estimate the melting point of c-husk and c-shell ash pellets. The compressive strengths against temperature exposure of c-husk ash were observed to have a decreasing trend while c-shell ash showed an increasing trend. Although the peak compressive strengths were not identified, the melting points of c-husk ash and c-shell ash were estimated to occur at temperatures lower than 600°C and higher than 900°C, respectively. Exceeding these ash melting points during thermal conversion assures the occurrence of fouling and slagging problems.

Biomass characterization, prediction of fouling and slagging tendencies, and ash melting point determination evaluated that c-shell is a suitable feedstock for gasification while c-husk is more compatible with low-temperature conversion process focused on char production.

RECOMMENDATIONS

Ash compositional analysis, through calculation of empirical indices, proved useful to evaluate the fouling and slagging tendencies of biomass. However, actual studies characterizing the behavior of biomass ash under various gasification temperatures must be performed to verify the conclusions of this study.

The ash melting temperature of c-husk and c-shell must also be evaluated at temperatures lower than 600°C and higher than 900°C, respectively, to determine the gasification temperature at which fouling and slagging will likely occur. Furthermore, use of standard method following STN ISO 540 for ash melting temperature determination is highly recommended for future related studies to get more comparable results with other literatures.

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