

SOLID BIOFUEL CHARACTERIZATION AND ASH PROPERTIES OF ACACIA MANGIUM

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Acacia Mangium is a common industrial planted woody biomass in the tropical and subtropical climates. As an economically viable, agroforestry beneficial and environmentally sustainable bio-energy form, it has the potential to generate heat for thermochemical conversion systems. This article provides a comprehensive evaluation of its characteristics, physiochemical properties, ash composition and transformation phenomena. In accordance with the ISO/DIN guides for solid fuels, the standard methods were applied. The results of analyses solid biofuel showed the significant calorific value (19-20 MJ/kg); high volatile matter, relatively low ash content; and a low S content. X-ray analysis detected high values of Ca, K, Fe, Al and Si the ash-forming elements. Ash softening and fusion phenomena were observed, with heat generated continuously at constant rates (maintained at 550 ± 10 °C for 120 minutes and practically at 850 ± 10 °C for 240 minutes). The first signs of deformation were recorded at a temperature of approximately 1220 °C, with the melting point reached at 1310 °C, which was an advantage for a woody solid biofuel.

Keywords: *Acacia Mangium*, solid biofuel, wood pellets, ash fusion, ash properties

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1. Introduction

Acacia species, primarily *Acacia Mangium*, have become the fast-growing tree species planted throughout the tropics and subtropics in various schemes [1], not only involved towards the raw materials supply for pulp and paper industry and timber production, but also for agroforestry and environmental purposes [2-4]. Their wide usage in afforestation is attributed to the rapid growth rate, tolerance to a range of soil types and pH values, improving depleted soils rather than wood quality [5]. Planting has been implemented on an industrial scale, with the main diversity center of approximately 2.6 million hectares covered in Southeast Asia, mainly in Thailand [6], Malaysia [7], Indonesia and Laos [8, 9], in particular 1 million hectares in Vietnam [10-12], where elevation is 50-350 m mean annual temperatures are 12-35 °C, annual precipitation is 1200-1850 mm [13].

A number of feasibility studies have described the physical and mechanical wood properties of *Acacia Mangium*, including bulk density, durability, fiber length and adhesive performance in order to achieve technologically efficient and economically production benefit [14-16]. Meanwhile, the principal wood biochemical compositions, including cellulose, hemicellulose, lignin and moisture content of stem wood were also identified in several quantitative approaches [17, 18].

Moreover, in the growing interest of replacing conventional energy sources by bio-energy, *Acacia Mangium*, including clonal *Acacia* hybrid, is substantially a woody biomass resource, characterized as a viable solid biofuel option for heat and electricity generation [19-21]. Therefore, it is important to extend the technical knowledge to its biofuel characteristics, phys-

io-chemical properties, ash compositions and transformation phenomena, as the first relevant concern in all types of thermo-chemical conversion technologies and applications [22].

In accordance with the guidelines for solid biofuels, we measured calorific values, analyzed elemental compositions, volatile organic contents and ash properties, determined ash melting points and especially observed ash softening and fusion of *Acacia Mangium* specimens. The obtained results enabled us to define the behavior of this solid biofuel considerably during the pyrolysis, gasification and combustion stages. Thereby, comprehensive data set significantly supports the proper design, operation setting, flue gas emission control and further innovative options, enhancing eco-friendly production and utilization of *Acacia Mangium*.

2. Experimental

2.1. Solid biofuel characterization

The principle and efficiency of any thermo-chemical conversion process depends strongly on the fuel properties, and hence influences the end-use applications and further gaseous products control options [23]. In practice, the whole process of biomass utilization including material supply, fuel analysis, application design, system testing, gaseous emissions, etc., conditionally rely on the physical characteristics and chemical composition. The medium and large-scale systems are suitable to combust low-quality fuel, while the smaller units demand higher fuel quality concerning the homogeneity.

Beyond the convenience of reducing bulky volume for transport, the high-density and high-energy content

per unit volume are the key advantages of biomass pellets to be widely used [24]. The qualities of pellets vary widely, influenced mainly on the pre-treatment technologies applied, where drying is an essential step to increase the heat exchange efficiency [25, 26]. Depending on the fuel preparation process, the particle size distribution is normally homogeneous, appropriate for small-scale fuel-feeding system and thermochemical conversion units.

Relevant solid biofuel properties were determined according to the methods defined in EN 14961-1. Each sample was analyzed at least twice and the average value of the results was presented. Physical parameters are particle dimensions, bulk and energy density, higher and lower heating values and moisture content.

Figure 1 shows the use of 6-mm diameter *Acacia Mangium* pellets produced in Northern Vietnam. The total moisture content (in mass fraction of water referring to the wet sample) was determined by oven dry method according to CEN/TS 14774-2:2004. The amount of volatile matter in the fuel was given in mass fraction referring to the dry sample. The analysis was done according to CEN/TS 15148.

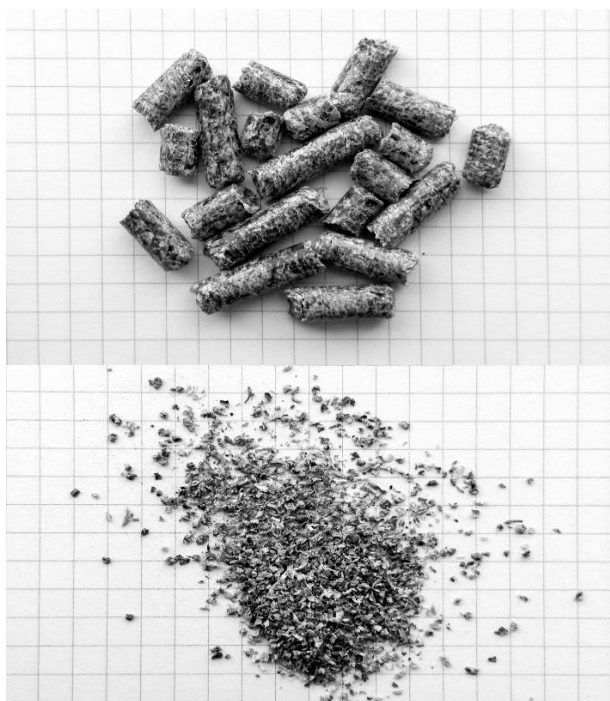


Figure 1. Available sample size of 6-mm for *Acacia Mangium* pellet and mill

Higher heating value (HHV or gross calorific value) and lower heating value (LHV or net calorific value) were given in MJ per kg, and results were presented referring to the dry sample. According to CEN/TS 14918, the HHV was determined using an adiabatic bomb calorimeter. Knowing the hydrogen content of the sample, the LHV was calculated on this basis.

The major constituents, i.e. carbon, hydrogen and nitrogen were determined according to CEN/TS 15104,

and given in mass fractions referring to the dry basis. For the analysis, an “elemental analyzer” was used. In this apparatus, a small amount of the sample (~2-3 mg) was oxidized with an excess of oxygen. The resulting products of CO₂, H₂O and NO_x are quantified after an adequate conversion and purification. Sulfur and chlorine were determined according to CEN/TS 15289. The sample was milled to fine particles, mixed thoroughly and pressed to pellets. These pellets were burned with an excess of oxygen and with the help of catalytic surfaces. The resulting gases were dissolved in deionized water and the solution was analyzed via inductively coupled plasma optical emission spectrometry (ICP-OES).

2.2. Ash properties

A number of researchers [27] reported that thermochemical conversion technologies involve a number of physical and chemical aspects of high complexity. Particularly, ash transformation during combustion of biomass is a very complex phenomenon, which can exhibit many essentially different scenarios [28]. The ash content value indicated a considerable influence on the technology applied, de-ashing process, transport, storage, utilization and disposal of the produced ash [29].

Each sample of *Acacia Mangium* was analyzed at least twice at the standard condition 550 ± 10 °C for 120 minutes (specified in CEN/TS 14775) and the average value of the ash content was presented in mass fraction referring to the dry sample. In addition, different sets of ash were prepared at 850 ± 10 °C and conditioned constantly for 240 minutes were analyzed for further practical comparisons.

Beside the standard methods to biofuels, the X-ray spectrometry on samples of conditioned ashes was applied for major and minor ash forming element analyses according to CEN/TS 15290 and CEN/TS 15297. The samples were milled to fine particles and underwent a microwave digestion using a mixture of HNO₃, H₂O₂, HF and HCl. The analyzed mass concentration in the resulting solution was determined using ICP-OES. Sodium was analyzed using Flame atomic absorption spectroscopy (FAAS).

Samples were melted in a Merck Spectrometer at a temperature of 1050 °C and placed on a stainless steel plate with a temperature of 400 °C. The PANalytical Axios-Advanced analyzer worked under a vacuum atmosphere with a rhodium anode, an excitation voltage of 50 kV, a tube current of 50 mA and loss on ignition by 1000 °C. Results of X-ray fluorescence (XRF) analysis indicated the elemental composition of the total sample calculated in oxides. Ash from tested feedstock was analyzed. From each of the fractions five samples for analysis were prepared. Separation was achieved to ensure the sample contained only impurities.

Ash softening and fusion processes were determined by optical standard lab-scale testing method according to CEN/TS 15370. Different sets of ashes were conditioned (maintained constantly at 550 ± 10 °C for

120 minutes and practically at $850 \pm 10 \text{ }^\circ\text{C}$ for 240 minutes) as showed in Figure 2.

Test pieces were pressed to the small geometric bodies while heat was generated continuously at the constant rates, then the changes in shapes were simultaneously recorded by the optical system (Figure 3). The ash melting behavior was described by characteristic temperatures measured at specified stages of the melting process, which are termed softening, spherical, hemispheric and flow temperatures.

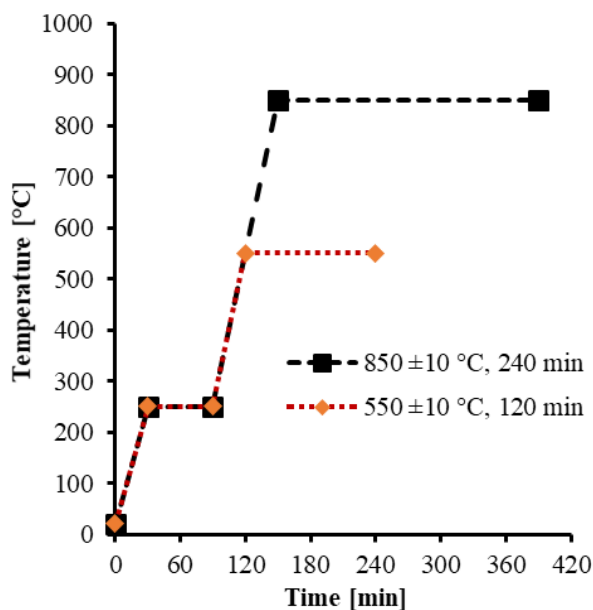


Figure 2. Ashing and conditioning of *Acacia Mangium* test portions in the different empirical conditions

3. Results and discussion

Table 1 summarizes the important values of investigated fuel. Recorded calorific values of approximately 19-20 MJ/kg indicate a high potential heat release and

the influence the process control during combustion, gasification and pyrolysis. Pellets low moisture content of 6-7 % specifies a minor influence in the combustion behavior; the volume of flue gas produced and average residence drying time before gasification takes place.

Table 1. Physiochemical properties of the tested *Acacia Mangium* as solid biofuel

General - mass fraction	Value	Unit
Moisture	6.94	[%]
Volatile - on dry basis	81.60	[%]
Fixed carbon - on dry basis	17.32	[%]
Ash content - on dry basis	1.08	[%]
Higher heating value	19913	[kJ/kg]
Lower heating value	18628	[kJ/kg]
Elemental analysis - mass fraction on dry basis		
Carbon (C)	49.97	[%]
Hydrogen (H)	5.85	[%]
Nitrogen (H)	0.33	[%]
Oxygen (O)	43.8	[%]
Sulphur (S)	0.02	[%]
Chlorine (Cl)	0.03	[%]

Main components of solid biofuel, carbon and hydrogen, were determined with mass fractions of 49.97% and 5.85% respectively on dry basis explain the high calorific value (19-21 MJ/kg) of *Acacia Mangium*, in comparison to other solid biofuel. High amount of volatile matter in *Acacia Mangium* with value of 81.6 % mass fraction indicates major part of this fuel was vaporized before homogeneous gas phase combustion reactions take place strongly influences the thermal decomposition and combustion behavior [30].

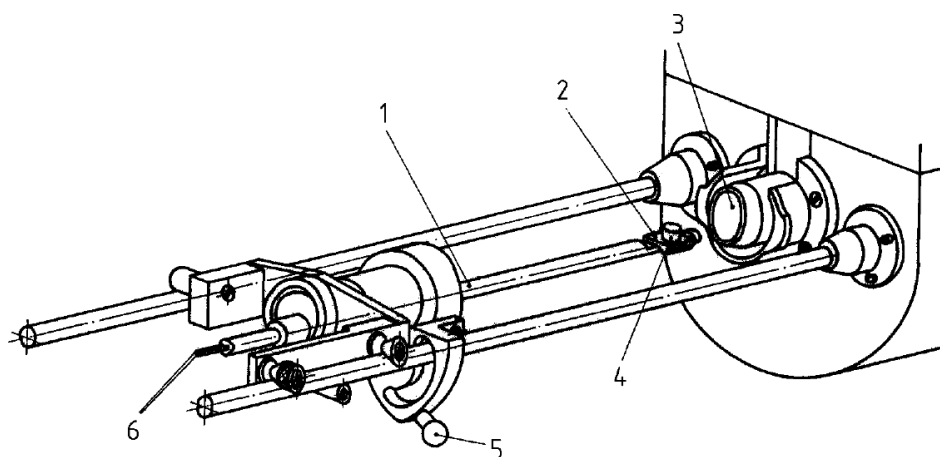


Figure 3. Optical lab-scale setup to characterize ash fusion specified in CEN/TS 15370
1-tube furnace; 2-specimen; 3-slide; 4-sample holder; 5-pivot lever; 6-thermocouple

Nitrogen oxides, HCl, Cl₂, alkali chlorides formation, gaseous compounds of SO₂, SO₃ and alkali sulfates released during the combustion process are important not only for emission control but also in corrosion processes [31]. Emission and environmental issues can be controlled with the adequate nitrogen, low chlorine and sulphur contents reported in the *Acacia Mangium* pellets (mass fraction of 0.33%, 0.03% and 0.02% respectively on dry basis).

The recorded value 1.08% in ash content of *Acacia Mangium* samples indicates a minor influence on the combustion technology applied, de-ashing process, transport, storage, utilization and disposal of the produced ash. This low value usually lead to low particulate matter emission, as minor influence on the heat exchanger design, cleaning system and dust control technology.

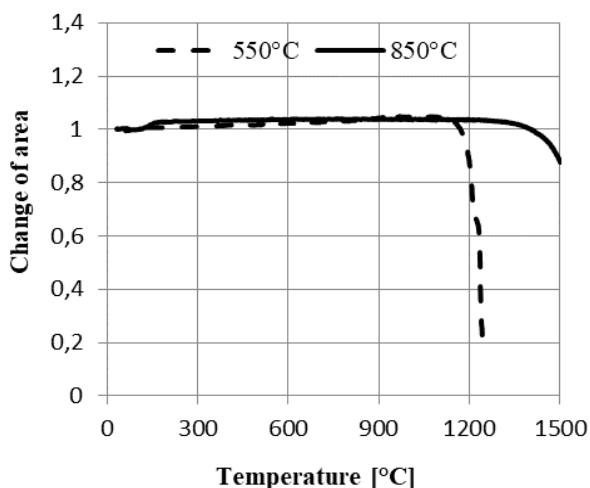


Figure 4. Observed difference in ash melting tendency

Figure 4 shows the remarkable changes in ash melting characteristic and tendency between tested conditions. The observed volume shrinking at 1220 °C only in the test specimens conditioned at 550 ± 10 °C for 120 minutes can be explained by the decomposition of major ash-forming elements (Fe, Mn, Ca, K, Cl, S, P, Al, Mg, Na and especially Si), by further oxidation (to higher oxidation states) and partial losses of volatile inorganic compounds. This phenomena practically recovered in the fly ash, and the decomposition of carbonates forming CO₂ mainly be released with other gaseous compounds.

Acacia Mangium specimens showed first signs of deformation were recorded at a temperature of approximately 1220 °C, with the melting point reached at 1310 °C, which was higher than the critical values of solid biofuel capable for the classic combustion or gasification processes in a fluidized bed. This high ash-melting point characterize *Acacia Mangium* as good solid biofuel for the modern combustion/gasification technologies, in terms of avoiding the sintering factors, decrease emission, minimize corrosion, maintain the operational safety control.

Figure 5 shows the phenomena described as the ash was spread out over the supporting tile in a thin layer. The height of this layer was defined as equal to one-fourth) of the base diameter ($H = 1/2r$ in CEN/TS 15370 considering bubbling effects as frequently occurred in other solid biofuels. Volume expanding and bursting of internal gas bubbles were not observed in the test pieces of *Acacia Mangium*. And thus, this obtained result confirmed minor influence on the accuracy of computerized image analysis and low uncertainties of characteristic temperature in ash melting behavior of *Acacia Mangium* pellets.

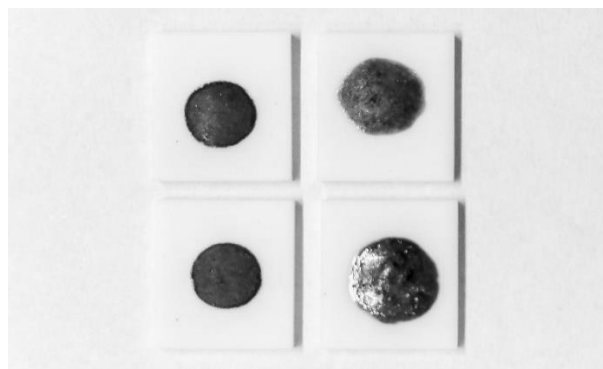


Figure 5. Test pieces observed in deforming states

Significant values in mass fraction of major cations and ash-forming elements especially Si, Ca, Mg, K, Na and P were determined. Figure 6 shows the considerable low alkali contents in the ash compositions while the relatively high Si value of 40% was detected. These contents are responsible for the high ash softening temperature, which in practical avoids the agglomeration of bed materials, minimize the risk of breakdown of the fluidized bed system and stop a combustion/gasification test at an early stage.

4. Conclusion

The study comprehensively extends recent knowledge in the nature, fuel characteristic, physiochemical property, ash forming phenomena and major compositions of *Acacia Mangium*. From this perspective, *Acacia Mangium* as a common planted woody biomass source covering Southeast Asia Pacific can be characterized as a dedicated biogenic solid fuel for further energetic utilization.

Verifying by significant calorific values, this woody solid biofuel showed a tremendous potential heat release for industries, utilities, communities and households if appropriate bio-energy technologies applied. Detected high ash softening temperature confirmed the advantages to avoid the technical issues in the thermochemical conversion applications. From this practical view point, specific elemental determination in the ash compositions is highly recommended to carry through further concerns subjected to slag formation and corrosion in the equipment.

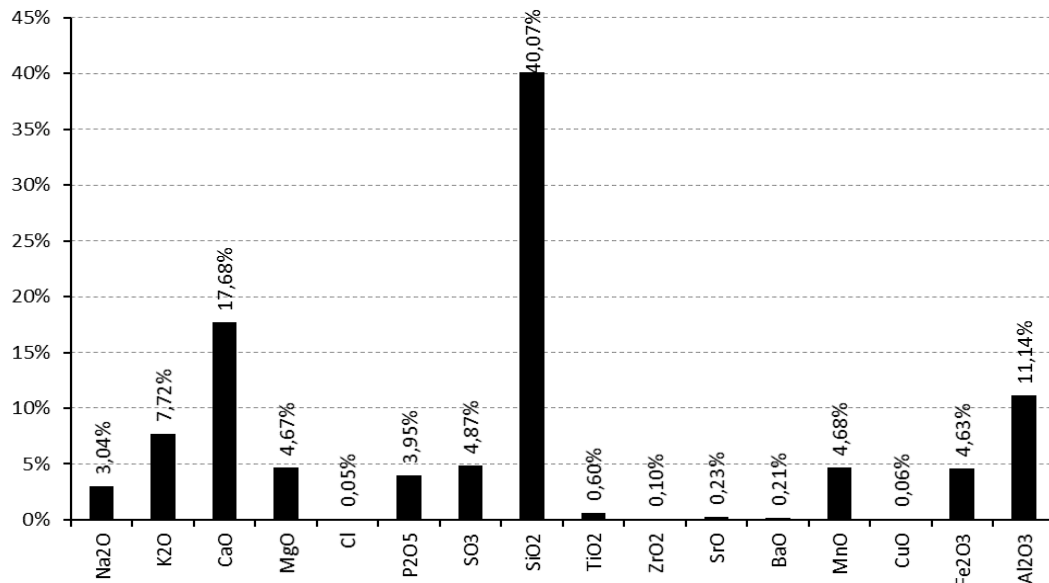


Figure 6. Ash elemental compositions in the specimens conditioned at 550 ± 10 °C for 120 minutes

The comparative evaluation outlined an extensive principal baseline for co-firing options of *Acacia Mangium* with other solid biofuels or viable conventional mineral fuels. Hence, it initiates further empirical investigations on modern biomass conversion technology targeting better efficiency performance. In addition, the shift to innovative applications using these biofuels should be carry out in corresponding to emission characteristic of solid and gaseous products. Above all, on highlighting the benefits of greenhouse gas reduction, *Acacia Mangium* can be a technically viable, economically efficient, and environmentally sustainable option in the future projection of bioenergy.

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