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Thermal and Ash Characterization of Indonesian Bamboo and Its Potential for Solid Fuel and Waste Valorization

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ABSTRACT. Bamboo has been widely used in Indonesia for construction, handicrafts, furniture and other uses. However, the use of bamboo as a biomass for renewable energy source has not been extensively explored. This paper describes the thermal and ash characterization of three bamboo species found in Indonesia, i.e. *Gigantochloa apus*, *Gigantochloa levis* and *Gigantochloa atroviolacea*. Characterization of bamboo properties as a solid fuel includes proximate and ultimate analyses, calorific value measurement and thermogravimetric analysis. Ash characterization includes oxide composition analysis and phase analysis by X-Ray diffraction. The selected bamboo species have calorific value comparable with wood with low nitrogen and sulphur contents, indicating that they can be used as renewable energy sources. Bamboo ash contains high silicon so that bamboo ash has potential to be used further as building materials or engineering purposes. Ash composition analysis also indicates high alkali that can cause ash sintering and slag formation in combustion process. This implies that the combustion of bamboo requires the use of additives to reduce the risk of ash sintering and slag formation.

Keywords: ash, bamboo, combustion, *Gigantochloa apus*, *Gigantochloa atroviolacea*, *Gigantochloa levis*

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1. Introduction

The use of biomass as a renewable energy source has increased in line with the limited resources of fossil energy. Although biomass has lower calorific value than coal, oil, or natural gas, the use of biomass as an energy source is more environmentally friendly because produced CO_2 gas will be used for growth of biomass so it does not contribute to the greenhouse effect (Demirbas 2005). Biomass can be divided into four types, namely woody plants, grass plants, aquatic plants, and manures (McKendry 2002a). Utilization of biomass into energy can through thermo-chemical process (combustion, gasification, pyrolysis) and bio-chemical process (fermentation, anaerobic digestion, mechanical extraction) (McKendry 2002b). Combustion process is the simplest way to utilize biomass as energy source.

Bamboo is one of biomass that can be used as an energy source because bamboo has calorific value almost equivalent to wood (Engler *et al*. 2012). Bamboo is a grass plant species included in the subfamily *Bambusoideae* and family *Andropogoneae*/*Poaceae* and has 1250 species. Bamboo is found in tropical and subtropical regions slightly in the lowlands to the highlands (4000 m above sea level). Bamboo plant height varies from the shortest of about 10 cm to 40 m (Scurlock *et al*. 2000). Bamboo has fast growth rate because bamboo can be harvested after 3-4 years (Kleinhenz & Midmore 2001). In Indonesia there are more than 35 species of bamboo. Most of the bamboo plants in Indonesia are sympodial, namely rods tend to get together in clumps and reproduce by rhizomes.

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Bamboo has been used as construction materials, handicrafts and furniture, pulp and paper industry, as well as musical instruments (Yudodibroto 1987).

To take advantage of bamboo as energy source by combustion process, it is necessary to understand the thermal and ash characteristics of bamboo. In general, high alkaline content in biomass ash can cause ash sintering and slag formation in the combustion process so that it needs to be added additives such as dolomite, kaolin, and limestone which can increase melting point of biomass ash (Llorente *et al*. 2008). This research studies the thermal and ash characteristics of three bamboo species, i.e. *Gigantochloa apus*, *Gigantochloa levis* and *Gigantochloa atroviolacea*. Combustion residues of bamboo by single combustion and co-combustion with kaolin as additive are also studied.

2. Materials and Methods

2.1 Materials

Three bamboo species, i.e. *G. apus*, *G. levis* and *G. atroviolacea* were obtained from Central Java, Indonesia. Bamboo was dried under the sun for 1 day before characterized and combusted.

Kaolin powder originated from Bangka Belitung, Indonesia. The major oxides in kaolin were SiO_2 (53.9%), Al_2O_3 (42.43%), Fe_2O_3 (1.17%) and K_2O (1.12%).

2.2 Thermal characterization

Fuel characterization of bamboo included proximate analysis and ultimate analysis, as well as calorific value analysis. Proximate analysis was carried out by ASTM D3172, ultimate analysis by ASTM D3176 and gross calorific value analysis by ASTM D5865.

Combustion characterization of bamboo used Thermal Gravimetric Analyzer (TGA) instrument, namely LINSEIS STA Platinum Series. Sample testing was conducted at room temperature up to 900 °C with a heating rate of 10 °C/min under air atmosphere.

2.3 Combustion process

Combustion process of bamboo and bamboo-kaolin mixture were carried out in a fixed bed furnace with capacity of 200 g. Bamboo was cut to size of 0.5x0.5x2 cm. Combustion of bamboo-kaolin mixture used mass ratio of bamboo:kaolin = 95:5. Combustion of bamboo-kaolin mixture was also carried out in an electric furnace at temperature of 500 ^{o}C for an hour to ensure that bamboo had become entirely ash.

2.4 Ash characterization

Chemical characterization of bamboo ash involved oxide composition analysis (SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, K_2O, Na_2O, MnO, TiO_2, P_2O_5, SO_3). Analysis of SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, K_2O, Na_2O and TiO_2 used SNI 13-3608-1994 method; MnO used Atomic Absorption Spectroscopy (AAS) method; P_2O_5 used spectrophotometric method and SO_3 used gravimetric method.

Combustion residues were analyzed by X-Ray Diffraction (XRD) instrument. XRD analysis was conducted with Bruker D8 Advance at room temperature under following conditions: 40 kV, 35 mA, CuKα radiation (wavelength λ_1=1.54060Å and λ_2=1.54439Å, intensity ratio α1/α2=0.5), and range of scanning angle 2θ from 5^{o} to 80^{o} at step size of 0.019^{o}.

3. Results and Discussion

3.1 Thermal characteristics

3.1.1 Proximate analysis, ultimate analysis and calorific value analysis

Proximate analysis results of three bamboo species denote that moisture content, ash content, volatile matter content, and fixed carbon content ranges between 8.13-8.89%, 2.45-3.29%, 70.31-72.71% and 16.07-18.35% as presented in Table 1. *G. atroviolacea* has the highest ash content and the lowest calorific value, whereas ash content and calorific value in *G. apus* and *G. levis* are relatively the same. The calorific values of three bamboo species are not much different from the calorific value of wood, i.e. *Leucaena leucocephala* and *Hibiscus tiliaceus*, so that bamboo also has potential to be used as renewable energy source like wood. Moreover moisture content in bamboo is also lower than that in wood. This result indicates that bamboo is easier to be combusted compared to wood (Jenkins *et al*. 1998).

Tabel 1
Proximate analysis and calorific value of selected bamboo and wood

Name of species	Proximate analysis (%)				Calorific value (cal/g)
	Moisture	Ash	Volatile matter	Fixed carbon	
G. apus	8.89	2.45	70.31	18.35	4151
G. levis	8.76	2.46	72.71	16.07	4161
G. atroviolacea	8.13	3.29	71.70	16.88	4086
*Leucaena leucocephala**	10.13	5.78			4197
*Hibiscus tiliaceus**	12	1.48			4196

*(Cahyono *et al*. 2008)

For ultimate analysis as shown in Table 2, the contents of carbon, hydrogen, nitrogen, sulphur and oxygen in *G. apus*, *G. levis* and *G. atroviolacea* bamboo indicate no substantial difference. Nitrogen and sulphur in fuel can generate pollutant gases, i.e. NOx and SOx, in combustion process. Three bamboo species contain nitrogen and sulphur less than 1%, respectively, indicating that bamboo utilization as an energy source does not cause major air pollution problems (Jenkins *et al*. 1998).

Tabel 2
Ultimate analysis of selected bamboo (%)

Name of species	Carbon	Hydrogen	Nitrogen	Sulphur	Oxygen
G. apus	44.29	6.16	0.53	0.10	46.47
G. levis	44.65	6.35	0.48	0.09	45.97
G. atrovio-lacea	44.11	6.26	0.47	0.07	45.80

3.1.2 Thermogravimetric analysis

Combustion characteristics of bamboo with thermogravimetric analysis exhibits that three bamboo species experienced four stages of thermal decomposition as shown in Fig. 1, i.e. temperature below 200 °C, temperature of 200-340 °C, temperature of 340-500 °C , and temperature of 500-900 °C.

Phenomenon of bamboo thermal decomposition can be explained from substances contained in bamboo. Bamboo contains lignin (20-30%), cellulose (40-50%), hemicellulose (25-30%), extractive material, and ash (Scurlock *et al*. 2000, Kumar & Chandrashekar 2014) as wood. According to Byrne & Nagle (1997), wood undergoes pyrolysis for hemicellulose at temperature of 200-260 °C, cellulose at temperature of 240-350 °C, and lignin at temperature of 280-500 °C.

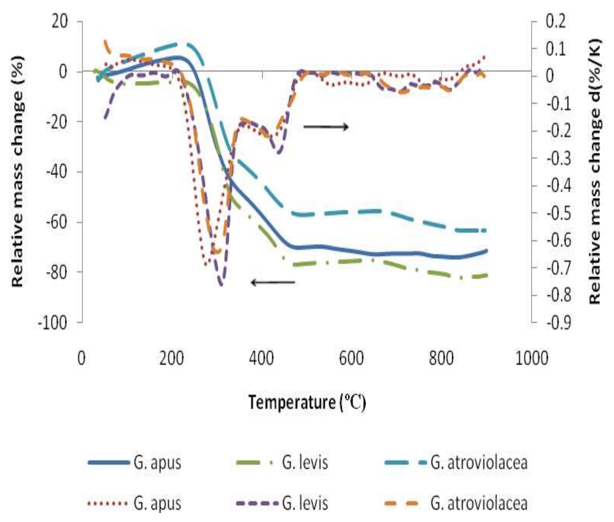

Fig. 1 Combustion profiles of selected bamboo

Bamboo initially undergoes evaporation of water and extractive materials at temperature up to 200 °C. In the next stage, at temperature of 200-340 °C, thermal decomposition of hemicellulose and cellulose are occurred. At this stage the mass loss for *G. apus*, *G. levis*, *G. atroviolacea* are 48.2, 47.9, 44.5%, respectively with maximum peak temperature are 276, 308, 295 °C, respectively. Furthermore, at temperature of 340-500 °C, thermal decomposition of residual cellulose and lignin takes place with mass loss for *G. apus*, *G. levis*, *G. atroviolacea* are 26.7, 24.6, 23.3%, respectively and maximum peak temperature are 434, 439, 422 °C, respectively. In the fourth stage, at temperature of 500-900 °C, thermal decomposition of residual lignin is occured and mass loss for *G. apus*, *G. levis*, *G. atroviolacea* are 4.7, 7, 7.8%, respectively.

3.2 Ash characteristics

3.2.1 Oxide composition analysis

The oxide compositions of selected bamboo ash are presented in Table 3. *G. apus*, *G. levis* and *G. atroviolacea* has high content of silicon so that bamboo ash has potential to be used further as building materials (brick, cement) or engineering purposes (catalyst, insulator) (Vassilev *et al*. 2013). Meanwhile potassium is dominant alkali in bamboo ash. The content of alkali in *G. apus*, *G. levis* and *G. atroviolacea* are relatively high as more than 25% that can lead to the risk of ash sintering and slag formation in combustion process of bamboo (Jenkins *et al*. 1998).

3.2.2 X-ray diffraction analysis

X-ray diffractograms for bamboo (*G. apus*) ash and kaolin are given on Fig. 2 and Fig. 3, respectively. Bamboo ash contains mineral phases, namely arcanite (K_2SO_4), sylvite (KCl), and quartz (SiO_2). This result is in accordance with oxide composition analysis that silicon and potassium are dominant in bamboo. Meanwhile, kaolinite is the dominant mineral phase in kaolin.

Co-combustion residue of bamboo-kaolin mixture denotes mineral phases both in bamboo ash (arcanite, sylvite, and quartz) and in kaolin (kaolinite) from X-ray diffractogram as shown on Fig. 4.

Co-combustion residue of bamboo-kaolin mixture further is burnt in electric furnace at temperature of 500 °C for an hour. X-ray diffractogram on Fig. 5 shows that there are arcanite, quartz, and kalsilite ($KAlSiO_4$) mineral phases.

Kalsilite ($KAlSiO_4$) is formed from the reaction between kaolinite ($Al_2Si_2O_5(OH)_4$) from kaolin with sylvite (KCl) and arcanite (K_2SO_4) from bamboo according to the following reaction (Konsomboon *et al*. 2011):

$$Al_2Si_2O_5(OH)_4 + 2KCl \rightarrow 2KAlSiO_4 + H_2O + 2HCl \quad \textbf{(1)}$$

$$Al_2Si_2O_5(OH)_4 + K_2SO_4 \rightarrow 2KAlSiO_4 + 2H_2O + SO_3 \quad \textbf{(2)}$$

Tabel 3
Oxide compositions of selected bamboo ash (%)

Name of species	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	MnO	TiO_2	P_2O_5	SO_3
G. apus	58.6	0.73	0.51	2.68	2.82	26.43	0.51	0.048	0.90	3.37	3.40
G. levis	45.8	0.22	0.26	4.50	3.94	34.16	1.49	0.090	0.71	4.22	4.61
G. atroviolacea	49.5	0.20	0.24	2.88	2.15	33.46	0.85	0.051	0.86	6.24	3.57

The reaction indicates that alkali in bamboo ash can be chemically bound by kaolin. Therefore, the addition of kaolin in bamboo combustion process can reduce the risk of sintering and slag formation.

Result of XRD characterization analysis also includes the quantification of proportions of total crystalline and amorphous phases as presented in Table 4. Further combustion of bamboo-kaolin mixture in the furnace at temperature of 500 °C increases the proportion of the amorphous phase. The combustion residue containing high silica (from bamboo) and alumina (from kaolin) with amorphous structure has possibility to be utilized as pozzolanic material for cement production (Rajamma *et al*. 2009).

Tabel 4
Material structure based on XRD analysis

Material	Structure	
	Crystalline (%)	Amorphous (%)
Bamboo (G. apus) ash	45.4	54.6
Kaolin	78.6	21.4
Combustion residue of bamboo-kaolin mixture	48.6	51.4
Combustion residue of bamboo-kaolin mixture at 500 °C	43.9	56.1

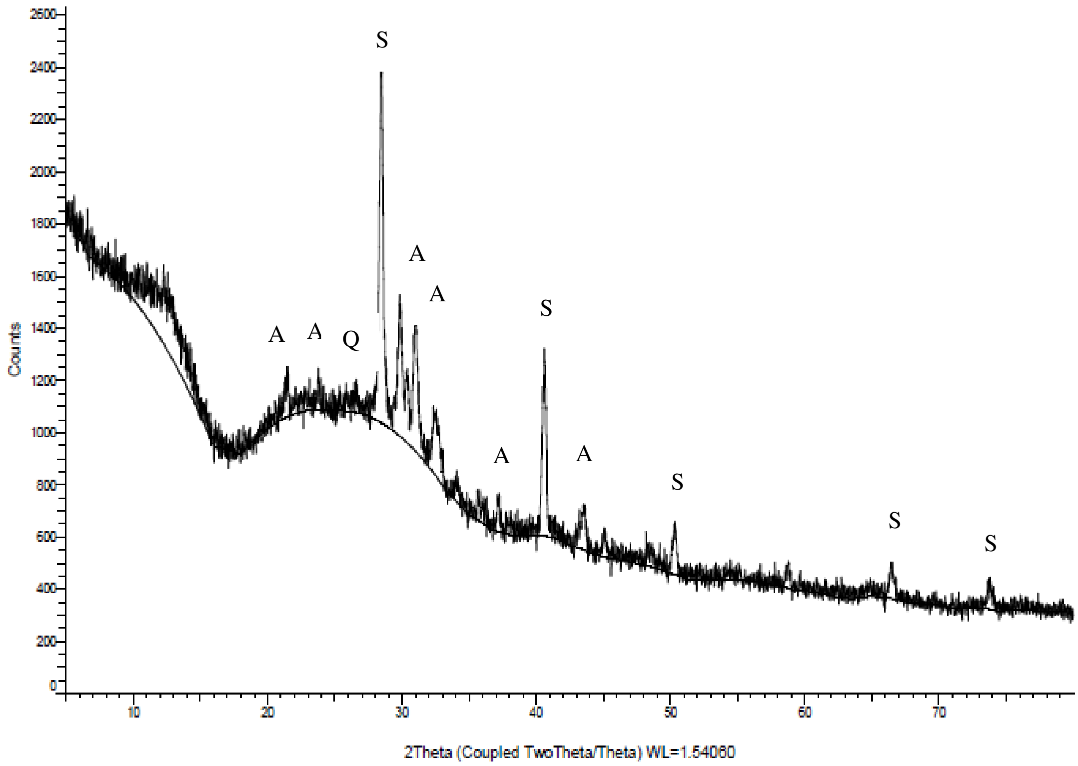

Fig. 2 X-ray diffractogram for bamboo (*G. apus*) ash (A = arcanite (K_2SO_4), S = sylvite (KCl), Q = quartz (SiO_2))

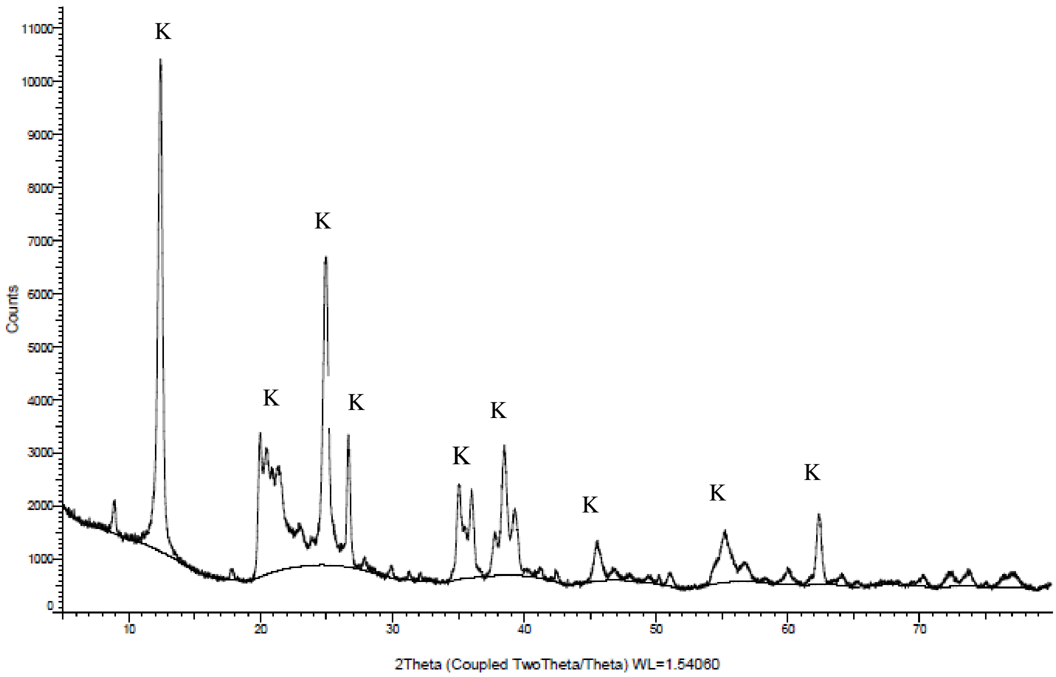

Fig. 3 X-ray diffractogram for kaolin (K = kaolinite ($Al_2Si_2O_5(OH)_4$))

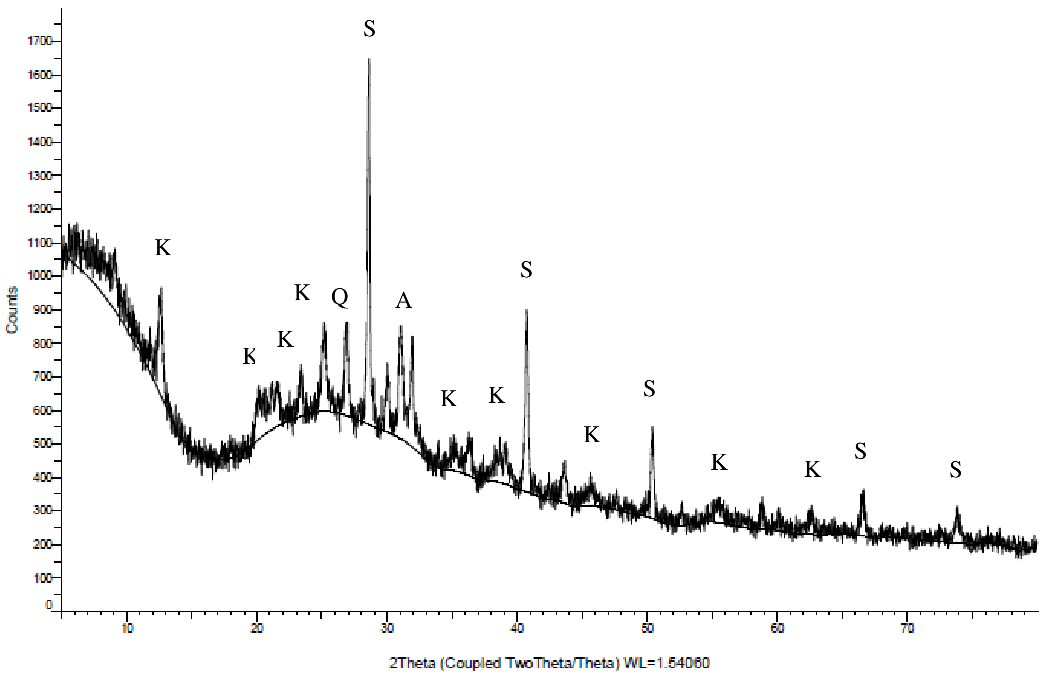

Fig. 4 X-ray diffractogram for combustion residue of bamboo-kaolin mixture (A = arcanite (K_2SO_4), K = kaolinite ($Al_2Si_2O_5(OH)_4$), S = sylvite (KCl), Q = quartz (SiO_2))

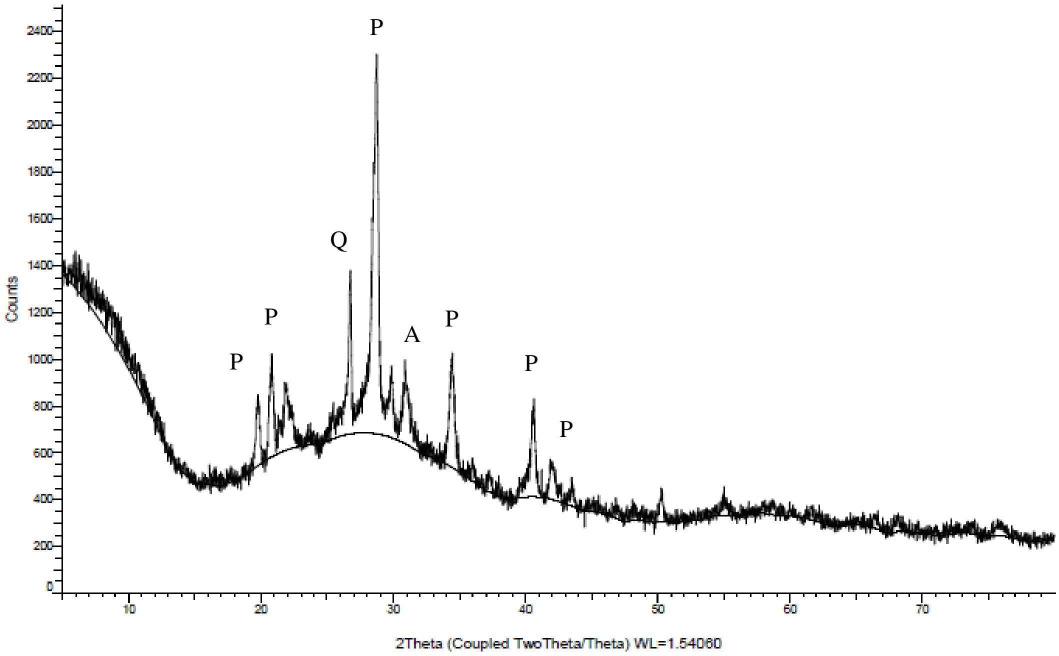

Fig. 5 X-ray diffractogram for combustion residue of bamboo-kaolin mixture at 500 °C (A = arcanite (K_2SO_4), P = kalsilite ($KAlSiO_4$), Q = quartz (SiO_2))

4. Conclusion

Thermal and ash characterization has been done for three bamboo species, i.e. *G. apus*, *G. levis* and *G. atroviolacea*. The selected bamboo can be used as renewable energy source because of their comparable calorific value with wood and low contents of nitrogen and sulphur. Bamboo ash can be utilized as building materials or engineering purposes due to high silicon content. Bamboo ash also contains high alkali that can cause sintering and slag formation in combustion process. The addition of kaolin in the combustion process of bamboo can reduce the risk of sintering and slag formation because it will bind alkali.

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