Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 21 February 2022 doi:10.20944/preprints202202.0244.v1

Article

A Comparative Evaluation of Combustion Characteristics of *Araucaria Cunninghamii, Intsia Bijuga* and *Pometia Pinnata* for Bio-Energy Source

Benson K. Gusamo* and Koniel A. Towalis

[1] Bulolo University College, P.O. Box 92, Bulolo, Morobe Province, Papua New Guinea
* Correspondence: benson.gusamo@pnguot.ac.pg

Abstract: Burning woody biomass for energy is gaining attention due to environmental issues associated with fossil fuels and carbon emission. The carbon released from burning wood is absorbed by plants and is carbon neutral. The purpose of this study was to investigate the combustion characteristics (heat calorific values and ash contents) of three timbers: *Araucaria cunninghamii*, *Instia bijuga* and *Pometia pinnata* and recommend for fuelwood. The test samples were sawdust particles (treatment) and solid woods (control) extracted from the heartwoods. The sawdust particles were oven-dried, sieved and pelletized into pellets using a hand-held pelletizing device, thus, forming cylindrical dimension (volume 1178.57 mm^3, oven dry density 0.0008 g/mm^3). While the solid woods were cubed and oven-dried (volume 1000.00 mm^3, oven dry density 0.001 g/mm^3). Prior to combustion in a semi-automatic bomb calorimeter, 90 test specimens (15 replicates per treatment and control per species) were conditioned to 14 % moisture content (at temperature 105 ºC) and weighed to a constant (unit) mass (1.0 g). The heat energy outputs and ash residues (of treatments) were analyzed statistically. The results indicated variability in heat energy outputs and ash residues between test specimens of the three species. Comparatively, the treatment specimens of *A. cunninghamii* produced higher calorific value (18.546 kJ/g) than the control (18.376 kJ/g) whilst the treatment specimens of *I. bijuga* and *P. pinnata* generated lower heat calorific values (17.124 kJ/g and 18.822 kJ/g) than the control (18.415 kJ/g and 20.659 kJ/g), respectively. According to ash content analysis, *A. cunninghamii* generated higher residues (6.3%) followed by *P. pinnata* (4.5%) and *I. bijuga* (2.8%). The treatment specimens of the three species could not meet the standard heat energy requirement (20.0 kJ/g) and thus, were unsuitable for fuelwood. However, the control specimens of *P. pinnata* generated equivalent heat energy (20.659 kJ/g) and could be a potential fuelwood.

Keywords: wood combustion; sawdust pellets; solid woods; heat calorific value; ash content; bioenergy; Papua New Guinea

1. Introduction

Burning wood for energy (heating, cooking, lighting, pottery) is an ancient and primitive practice. The practice declined in most developed nations when fossil fuel was discovered in the 1900s [1]. Today, burning fuelwood (firewood and charcoal) for heating and cooking is a cheap necessity and widely applied in developing countries [2]. For instance, 85% population of Papua New Guinea (PNG) depends on fuelwood [3]. About 90% of fuelwood is used in tropical countries [4] while 60 to 80% share of wood consumption is fuelwood in the developing world [2]. Also, an estimated 53% of wood is consumed worldwide for energy [5]. Additionally, it is projected that 18% of the world's energy consumption will be sourced from wood by 2050 [6]. Further, more than half the world's population rely on forest biomass for energy [7]. Furthermore, 2.7 billion population will rely on biomass energy by 2030 [8]. Apart from household needs (heating and cooking), a substantial share of fuelwood is consumed by agri-industries for curing their products [1].

Presently, global demand for fossil fuel-derived energy is increasing due to the growing population and industrialization. By 2040, energy demand will rise by 30% [9]. However, the issue with burning fossil fuel for energy is linked with the emission of greenhouse gas (GHG) and environmental degradation. Environmental issues as well as limited natural oil reserves and high costs of petroleum products have triggered interest in 'green energy' [10-12]. The focus has been on renewable energy and forest biomass is identified as a potential bio-energy source [13]. Biomass, the 4th largest contributor of bio-energy [9], has the advantages of being renewable and sustainable, abundantly available, and environmentally benign [14]. Also, biomass has low embodied energy and could be cost-effective [1], technically feasible and economically viable [15]. Currently, the industrial bio-energy market is increasing in Europe and the US and Eastern Europe biomass industries are manufacturing million tons of wood pellets to supply the market [16]. Also, South Korea is subsidizing forest biomass for renewable energy [16]. Next, Australia intends to supply the European energy market with 15,000 tons of charcoal briquettes made from eucalyptus [17]. As far as GHG is a concern, biomass combustion releases carbon which has a similar effect as carbon emitted from fossil fuels [18,19]. Comparatively, carbon released from burning biomass is lower than fossil fuels [20,21]. For example, burning 1.0 t of biomass generates 1.5 t of CO_2 on average [18]. Also, IRENA [22] reported 36.9 Gt of CO_2 released in 2017. Additionally, Yoshida et al. [23] compared CO_2 emitted from burning biomass and conventional fuels as: biomass (10 g C MJ^{-1}), gasoline (150 g C MJ^{-1}), and diesel (140 g C MJ^{-1}). Further, bio-energy advocators asserted that carbon emission from biomass combustion is absorbed by growing trees and the process is 'carbon neutral' with zero net carbon emission [19]. However, many environmental scientists argued that the carbon neutrality concept is erroneous, misleading, and could destabilize the climate [19,24-27].

Combustion characteristics (heating value and ash content) vary significantly within and between timber species. These are attributed to heterogeneous physical nature and chemical composition of wood. For instance, wood density and chemical constituents e.g. high carbon content, lignin content, and extractives affect heating values [28-32]. In addition, high density woods with long fibre and thick cell walls, low holocellulose and high extractive and lignin contents have high heating values and thus, are potential materials for bioenergy [33]. Comparatively, resinous softwoods yield higher heating values than hardwoods [30,34,35]. Further, wood's hygroscopic nature and moisture content, temperature, and structural features influence combustion and flammability [34,36]. After combustion of biomass, the remains are ash content. Ash content as mass of biomass material that remains after high temperature burning in the presence of oxygen expressed as percentage of moisture free weight of wood [1]. It is expressed that ash content is an important parameter that determines calorific value [37]. High ash content reduces effect of fuel quality and affects efficiency of the combustion process. Furthermore, the properties of biomass to consider during processing for energy are calorific value, proportions of carbon and volatiles, ash content, alkali metal content, and cellulose/lignin ratio [38].

Globally, combustion characteristics of various forest species have been studied extensively for their fuelwood potentials. For categorizing a species for its potentiality as fuelwood, Johnathan et al. [37] stated 20.0 kJ/g heat calorific value as a standard. The authors reported 21.7 kJ/g (as average heating values) for 31 PNG species and recommended as potential fuelwoods. Also, species with fuelwood potentials have been selectively cultivated in woodlots and plantations to provide feedstocks for biofuel industry around the world. For instance, in Poland, three species are managed on a short rotation plantation for bio-energy [39]. Brazil has the world's largest Eucalyptus plantation devoted for bio-energy [8], India launched 600,000 ha biofuel plantations on wastelands from 2004-2005 [40], and in Sri Lanka a plantation (101.6 ha) was tried with 12 different species for fuelwood [41]. While in PNG, a bio-energy project has established 2,400 ha plantation (as of 2018) of *Eucalyptus pellita* and *Acacia* spp. for electricity generation [42] and is anticipated to secure 22,000 ha on a long term basis [43]. Additionally, small business opportunities

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 21 February 2022 doi:10.20944/preprints202202.0244.v1

were identified in charcoal production from short-rotation agroforestry practices in PNG [44].

Technologies are available to convert biomass residues/wastes from primary industries for biofuel products [45]. Agroforestry residues include shavings, slabs, sawdust, and off-cuts from forest industries [46] and rice and wheat husks, kernels, and palm oil wastes from agricultural industries [47-50] are prime raw materials for biofuels. These feedstocks are converted into biofuel products (charcoal, briquettes, pellets, and biogas) using modern technologies e.g. combustion, carbonization, pyrolysis, gasification, fermentation, biochemical, and transesterification [31,51]. Prior to conversion into biofuels, pre-treatments (defiberization, densification, pelletizing, and torrefaction) are given to improve biomass characteristics and hence, increase heat energy output [31,51]. In this case, solid materials are reduced to fine particles, dried, solidified into pellets and torrified [51-54]. Further, advance technologies are adopted for production of biofuel liquids on industrial scales e.g. fermentation of sugarcane wastes for bioethanol [55]. Globally, Brazil is the largest bioethanol producer after the USA [56]. Additionally, vegetable oils derived from plants' seed kernels [57,58] are converted into biodiesel through transesterification for energy source [59-64].

This case study examined the combustion characteristics (heat calorific values and ash contents) of a plantation-grown *Araucaria cunninghamii* Ait. and natural hardwoods *Intsia bijuga* Kuntze, and *Pometia pinnata* Forst. The specific objectives were to:

- extract test samples from the heartwoods of the test species i.e. sawdust particles and densify into pellets (treatment) and solid wood cubes (control)
- make comparative assessment of heat energy outputs between the sawdust pellets and solid woods and analyze the ash contents of the sawdust pellets.
- compare the heat calorific values and ash contents of I. bijuga and P. pinnata with published data
- make recommendations on the potential of the species for fuelwood.

Ultimately, the findings of this research intended to provide basic data on combustion characteristics of the test species so that their potential for generating energy could be explored. Also, opportunities to maximize the utilization of sawmill residues of the three species for producing wood pellets could be identified.

2. Materials and Methods

2.1. Test Timber Species and Sampling

The test candidate timbers are three indigenous species: *Araucaria cunninghamii* Ait. (Hoop pine), *Intsia bijuga* Kuntze. (Kwila), and *Pometia pinnata* Forst. (Taun). *A. cunninghamii* (Araucariaceae family) is a coniferous tree and has low to medium weight and hardness [65]. The other two species are hardwoods i.e. *I. bijuga* (Fabaceae family) has hard and heavy woods while *P. pinnata* (Sapindaceae family) has medium weight and hardness [66]. Wood density, chemical analysis, and combustion characteristics of the species based on PNG grown materials are given (Table 1).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 21 February 2022 doi:10.20944/preprints202202.0244.v1

Table 1. Physical and chemical properties of test species

Test Species	Physical Property†	Chemical Analysis (%)**	Combustion/Energy Values‡	
	Density (kg/m³)*	α-Cellulose/Holocellulose/Klason Lignin	AC (%)	HCV (kJ/g)
A. cunninghamii	440-520	Nil	Nil	Nil
I. bijuga	670-800	31.8/65.0/31.6	1.6	20.431
P. pinnata	625-700	44.6/69.0/30.5	0.8	21.095

Sources: †Eddowes [66]; **Pillotti [67]; ‡Johnathan et al. [37]; *Density at 12% moisture content, AC – Ash content, HCV – Heat calorific value. Note: The chemical and combustion properties of *A. cunninghamii* are unknown to date.

The three test species were sourced from: Bulolo plantation (*Araucaria cunninghamii*) and Wafi natural forest (*Intsia bijuga* and *Pometia pinnata*) of Morobe Province, PNG. The three logs of test species were taken to the processing mills for lumber production. After processing, a 1.0 m sawn board and a 10 kg sawdust of each species (i.e. three pieces 1.0 m sawn boards and three 10.0 kg sawdust) were collected from two sawmills (PNG Forest Products LTD, Bulolo, and Timber and Forestry Training College, Lae). The sawn boards and sawdust were selectively obtained from heartwood portions of the logs. The sawn boards and sawdust samples were then stored in a controlled laboratory condition in order to avoid infestation from micro-organisms.

2.2. Experimental

2.2.1. Preparation of Solid Wood Specimens

A 1.0 m sawn board per species was cut into 30 cm sample lengths, placed in an oven drier at 105 ºC and dried to 14 % moisture content (MC) following the procedure used by Jonathan et al. (2016). The samples were removed and placed in a desiccator to cool whilst avoiding moisture uptake and re-cut into solid wood specimen dimensions (10 mm cubed per specimen). All specimens were then returned to oven drier for further conditioning to constant weights of 1.0 g before combustion test. A solid wood (cubed) specimen had a volume of 1000 mm³ which was computed using an equation for cuboid. A total of 45 replicates (15 specimens per test species) were prepared for experiment (Table 2).

2.2.2. Preparation of Sawdust Particles: Sieving and Pelletizing

Following ASTM D2013-72 standard [68] (with some modifications), the sawdust particles of the three species were sieved by passing through a 250 µm sieving tray. The fine particles were collected, placed in an oven drier at 105 ºC temperature and conditioned to 14 % MC. The MC of the fine sawdust particles was computed (equation 1).

$$\mathrm{MC} = \frac{M2-M3}{M2-M1}\, x\, 100 \tag{1}$$

Where: MC – moisture content (%), M1 – mass of weighing dish and lid (g), M2- mass of weighing dish and lid plus sawdust before drying (g), and M3 – mass of weighing dish and lid plus sawdust after drying (g).

After conditioning, the fine particles were composed and compacted following Harun and Afzal [48]. In this case, the fine sawdust particles of the test species were weighed to 1.0 g and placed in a pelletizing device (pelletizer). The fine particles were filled in a steel cylinder (height 15 cm and diameter 1 cm) of the pelletizer and lightly pressed with hands. In the pelletizer, steel cylinder containing fine particles was tightened with a

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 21 February 2022 doi:10.20944/preprints202202.0244.v1

screw-like knob until tight enough to compact and solidify the particles. The resultant products were highly densified sawdust pellets of cylindrical dimensions (Fig. 1).

Figure 1. Densified sawdust pellets.

The volumes of a cylindrical pellets were determined using equation 2.

$$V = \pi r^2 h \quad (2)$$

Where: V – volume of pellet (mm³), r – radius of pellet (mm), and height of pellet (mm)

The density of pellets was calculated (equation 3) from the mass divided by volume as per Artemio et al. [52].

$$D = \frac{M}{V} \quad (3)$$

Where: D - pellet density (g/mm³), M - mass of pellet (g), and V - volume of pellet (mm³)

A total of 45 replicates (15 sawdust pellets per species) were produced for experiment (Table 2).

Table 2. Control and treatment specimens and their replicates per test species

Test Species	Control	Treatment
Araucaria cunninghamii	15	15
Intsia bijuga	15	15
Pometia pinnata	15	15
Total	**45**	**45**

The physical characteristics (mass, volume, and density) of the treatment and control specimens for the three test species were determined prior to combustion experiment (Table 3).

Table 3. Physical characteristics of solid wood and sawdust pellet of the test species

Test Specimens	Mass (g)	Volume (mm³)	Density (g/mm³)
Solid woods*	1.0	1000.00	0.001
Sawdust pellets**	1.0	1178.57	0.0008

*control, **treatment,

2.2.3. Experimental Design

The design of the experiment was based on complete randomized design. In this experiment, sawdust pellets were used as treatment while the solid wood cubes were control. A total of 90 specimens for the three test species (15 replicates each for control and treatment per species) were prepared for combustion experiment as highlighted in Table 2.

2.2.4. Combustion Test

The sawdust pellets (treatment) and solid woods (control) underwent combustion in an Indian-made semi-automatic (oxygen) bomb calorimeter (Rajdhani Digital Bomb Calorimeter Model RSB-5) following the procedure applied by Jonathan et al. [37].

An individual specimen of treatment and control (1.0 g) was placed in a crucible to the bomb electrodes. The specimen was tied to ignition rope with the (both) end(s) tied to ignition wire (6 cm length) whilst the bomb head was on its support. The ends of ignition wire attached to electrodes were to facilitate complete specimen combustion. Using a syringe, a 1 ml of distilled water was squeezed into the bomb cylinder before the bomb was lowered and tightly closed to avoid leakage of oxygen. The oxygen was allowed to flow into the combustion cylinder. Then the combustion cylinder was lowered into a calorimeter bucket filled with 2100 ml of distilled water. In the head of combustion cylinder, there were positive and negative nodes which were connected to cables to activate ignition. The calorimeter bucket was closed and the thermometer sensor was then lowered into the bucket. The power was switched on to start the auto temperature (adjustment) and stirring motor. The mass of the individual test specimen was adjusted within the device system before firing of the bomb using ignition switch. It took about 5 mins for the complete combustion of the specimen. The heat calorific value (thermal energy) per specimen (solid wood and sawdust pellet) for the test species was generated automatically from the semi-automatic bomb calorimeter and was printed out. For every individual specimen combusted, heat calorific value (kJ/g) was calculated using equation 4 as per ASTM D5865-13 standard [69].

$$\mathrm{GCV} = \frac{We\Delta T-(W1(4.18)+W2(0.335))}{M} \qquad (4)$$

Where: GCV – gross calorific value (kJ/g), M – mass of specimen (g), We – water equivalent (ml), W1 – weight of cotton thread (g), W2 – weight of fuse wire (g), and ΔT – rise in temperature (ºC)

2.2.5. Ash Content Test

A separate experiment was conducted to determine the ash content of the test species. The sawdust samples were placed in an oven drier (105 ºC) and monitored until constant weights (1.0 g) were achieved. An individual sawdust pellet (weighing 2.0 g) was replicated (15 sawdust pellets per species) and a total of 45 specimens were prepared from the dried samples. Following the ASTM D1102-84 standard [70] and procedure applied by Chandrasekaran et al. [71], the sawdust pellets were placed in a porcelain crucible using a muffle furnace for 2 h at 580 ºC temperature. The 45 specimens of the three species underwent combustion and the remains were collected and analyzed for the ash contents. The amount of ash content per species was determined (equation 5) in accordance with Kamperidou et al. [72]:

$$AC = \frac{M3-M1}{M2-M1}\,x\,100 \qquad (5)$$

Where: AC – ash content (%), M1 – mass of empty crucible (g), M2 – mass of crucible plus test specimen (g), and M3 – mass of crucible plus ash

2.3. Statistical Analysis of Data

The heat calorific value (kJ/g) generated by individual specimen of the treatment and control specimens was compiled as raw data. The results (raw data) were statistically analyzed for their minimum, maximum, mean, and standard deviations (Table 4). Also, a boxplot analysis (using Special Package for the Social Sciences (SPSS) Version16.0) was used to display the spread of heat calorific values (range, median, quartiles, and interquartile range) of treatment and control specimens of the test species (Fig. 3). Additionally, a one-way analysis of variance (ANOVA) was performed to test any significant variations (at 5% significance level) of the mean calorific values between the treatment and control specimens for the test species (Table 5). Further, the remains (ash contents) of the test species were statistically analyzed and presented (Tables 6 and 7).

3. Results and Discussion

3.1. Rationale for Composing Test Specimens to Unit Mass for Heating Values

The sawdust pellets (treatment) and solid woods (control) of the three species were conditioned (14 % MC) and weighed to a constant (unit) mass of 1.0 g. Due to the differences in the test specimen, their volumes and oven dry densities differed (Table 3). The heat (and heating value) is measurable from the complete combustion of a unit mass (1.0 g or 1.0 kg) of wood [34]. Theoretically, the amount of heat energy that could be produced from burning a unit mass (1.0 g) of dried woody substances (in treatment and control specimens) could be measured [34].

3.2. Comparative Heat Energy Outputs between Test Specimens of the Three Species

A comparison was made for heat energy outputs (calorific values) between the sawdust pellets (treatment) and solid woods (control) of the three species. According to the results of the experiment (Table 4), higher heat (mean) calorific value was recorded for sawdust pellets (18.546 kJ/g) than the solid woods (18.376 kJ/g) in *Araucaria cunninghamii*. Lower heat calorific values were observed for the sawdust pellets of *Pometia pinnata* and *Intsia bijuga* (18.822 kJ/g and 17.124 kJ/g) compared to their solid woods (20.659 kJ/g and 18.415 kJ/g), respectively. In this case, the solid woods of *P. pinnata* and *I. bijuga* generated higher heat energies than the sawdust pellets except for *A. cunninghamii*.

Table 4. Heat energy output of sawdust pellet and solid wood specimens of test species

Test Species		**Statistical Analysis of Heat Calorific Values (kJ/g)**			
		Minimum	**Maximum**	**Mean**	**STDEV***
A. cunninghamii	Sawdust pellets (T)	16.421	22.445	18.546	1.71
	Solid woods (C)	13.596	23.316	18.376	3.00
I. bijuga	Sawdust pellets (T)	14.030	23.936	17.124	2.42
	Solid woods (C)	16.948	20.499	18.415	1.02
P. pinnata	Sawdust pellets (T)	13.029	23.149	18.822	2.44
	Solid woods (C)	16.019	24.669	20.659	2.17

T - treatment specimens, C – control specimens, *standard deviation

According to Table 5, the ANOVA test ($p=0.05$) revealed a significant difference ($p<0.038$) between the mean heat value outputs between the sawdust pellets and solid woods of *P. pinnata*. On the other hand, there were no significant variations noted for the mean heat value outputs between the sawdust pellets and solid woods of *A. cunninghamii* ($p>0.850$) and *I. bijuga* ($p>0.067$).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 21 February 2022 doi:10.20944/preprints202202.0244.v1

Table 5. ANOVA of heat calorific value of wood pellet and solid wood of test species

A. cunninghamii	**Sum of Square**	**df**	**Mean Square**	**F**	**Sig.**
Between group	0.216	1	0.216	0.036	0.850
Within group	167.008		28 5.965		
Total	167.224	29			
I. bijuga					
Between group	12.51	1	12.51	3.632	0.067
Within group	96.447	28	3.445		
Total	108.958	29			
P. pinnata					
Between group	25.309	1	25.309	4.751	0.038
Within group	149.152		28 5.327		
Total	174.461	29			

Also, the minimum and maximum heat energy outputs between the test specimens of the three species were compared (Table 4). According to the heat energies of sawdust pellet specimens (treatment), the minimum (lowest) heat calorific values were obtained for *P. pinnata* (13.029 kJ/g) followed by *I. bijuga* (14.030 kJ/g) and *A. cunninghamii* (16.421 kJ/g). The maximum heat calorific values generated for sawdust pellets were: *I. bijuga* (23.936 kJ/g) followed by *P. pinnata* (23.149 kJ/g) and *A. cunninghamii* (22.445 kJ/g). As for solid woods (control) minimum heat calorific values produced were: *A. cunninghamii* (13.596 kJ/g), *P. pinnata* (16.019 kJ/g) and *I. bijuga* (16.948 kJ/g). The maximum heat calorific values yielded for the solid woods were: *P. pinnata* (24.669 kJ/g), *A. cunninghamii* (23.316 kJ/g) and *I. bijuga* (20.499 kJ/g).

Further, a boxplot analysis (Fig. 3) was conducted to demonstrate the spread of medians and ranges of sawdust pellets (treatment) and solid woods (control) of the test species. Accordingly, the median and range of *P. pinnata* (treatment and control) exhibited wider spread than the *A. cunninghamii* and *I. bijuga*. Comparatively, *A. cunninghamii* has a wider spread (range and interquartile range) for solid woods followed by *P. pinnata* and *I. bijuga*.

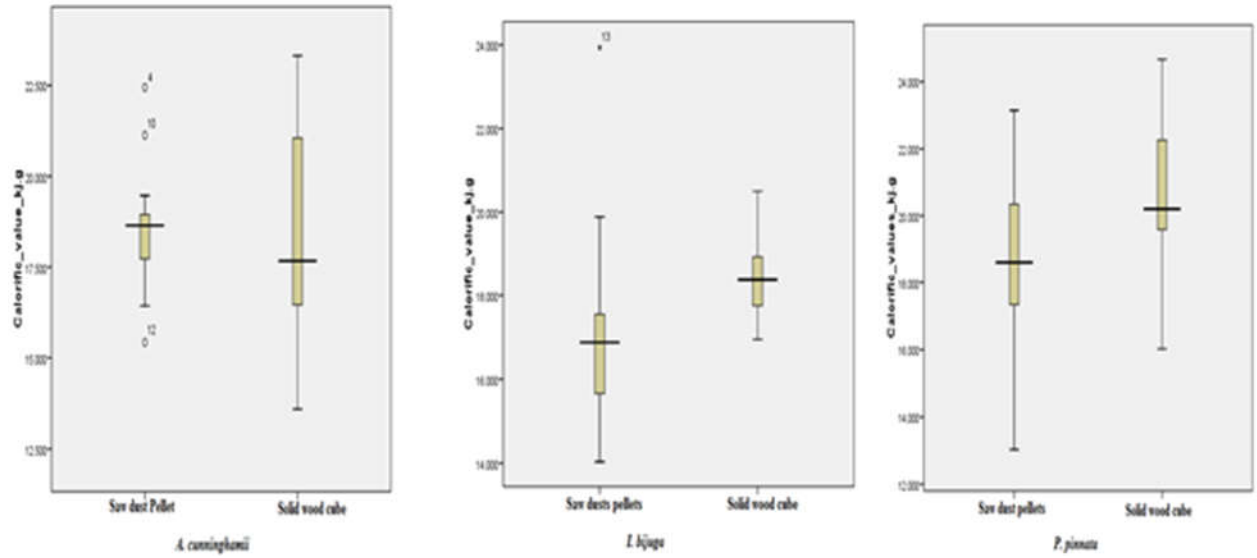

Figure 3. Boxplot analysis of heat energy output of treatment and control specimens of test species.

3.3. The Effects of Physical and Chemical Properties of Test Specimens on Heat Energy Outputs

The heat energy outputs between the sawdust pellets (treatment) and solid woods (control) varied markedly although the test specimens were weighed to constant (unit) mass of 1.0 g. The major contributing factors to generating different heat calorific values (treatment and control) were due to physical characteristics i.e. specimen volumes and oven dry densities e.g. treatment (vol. 1178.57 mm^3 and density 0.0008 g/mm^3) and control (vol. 1000.00 mm^3 and density 0.001g/mm^3). The difference in oven dry density (0.0002 g/mm^3) between treatment and control specimens had effect on the heat energy outputs. For instance, high heat energy output in sawdust pellets of *A. cunninghamii* (18.546 kJ/g) was attributed to high specimen volume and oven dry density, pelletizing (densification) as well as resin contents. This observation correlated with the studies [31,73] that reported high heat energies from high density woods and solidification of particles.

Next, opposite trends were noted for *I. bijuga* and *P. pinnata* where solid woods generated high heat energies (18.415 kJ/g and 20.659 kJ/g) despite high oven dry densities compared to the sawdust pellets (17.124 kJ/g and 18.822 kJ/g), respectively. This could be explained by the presence of extractives in the solid woods of *I. bijuga* and *P. pinnata*. Similar explanations were pointed out by early researchers [29,31,37]. In addition, lower heat energies observed for sawdust pellets of *I. bijuga* and *P. pinnata* could be due to the use of immature heartwood and sapwood particles in the sawdust mixtures, loss of volatile (extraneous) substances during log processing, storage, drying, and pelletizing processes, and use of hand-held mechanical device for pelletizing and densification of the sawdust particles.

3.4. Comparing Heat Energy Outputs of Intsia bijuga and Pometia pinnata with Published Data

The heat calorific values generated by *Pometia pinnata* and *Intsia bijuga* of this study were compared with the published data (Table 1) [37]. As per the results (Table 4), heat energy outputs exhibited for sawdust pellets and solid woods: *P. pinnata* (18.822 kJ/g - 20.659 kJ/g) and *I. bijuga* (17.124 kJ/g - 18.415 kJ/g) were lower than the findings of Johnathan et al. [37] for the same species i.e. *P. pinnata* (21.095 kJ/g) and *I. bijuga* (20.434 kJ/g). The low heat energy yields of the two species were due to specimen dimensions used in this study compared to Johnathan et al. [37]. For instance, Johnathan et al. [37] applied large specimens (15 x 15 x 20 mm) while this study used cuboid (10 x 10 x 10 mm) for combustion. In addition, this study suggested that parameters (specimen age, moisture content, biochemical properties, and application of different of bomb calorimeter models) may have contributed to differences in the heat energy outputs.

3.5. Ash Content Analysis and Effect on Heat Energy Outputs of Test Species

The ash content analysis (Table 6) of the sawdust pellets indicated that *Araucaria cunninghamii* yielded the highest ash remains (6.3%) followed by *Pometia pinnata* (4.5%) and *Intsia bijuga* (2.8%).

Table 6. Ash content analysis of ash contents of sawdust pellets of test species

Test Species	Statistical Analysis of Ash Contents (%)			
	Minimum	Maximum	Mean	STDEV‡
A. cunninghamii	5.736	7.181	6.345	0.473
I. bijuga	2.399	2.946	2.793	0.140
P. pinnata	4.269	4.909	4.503	0.179

‡standard deviation

When comparing ash contents and heat energy outputs (Table 4), high ash yielding species *A. cunninghamii* (6.3%) and *P. pinnata* (4.5%) produced high heat calorific vlaues (18.546 kJ/g and 18.822 kJ/g, respectively) compared to *I. bijuga* (2.8%) with heat calorific value of 17.124 kJ/g. The findings disagreed with many studies [29,31,37] that claimed lower the ash residues the higher would be the heat energy values. Additionally, an ANOVA test ($p=0.05$) revealed significant difference ($p<0.00$) in the ash contents of the three species combusted in the experiment.

Table 7. ANOVA of ash content of sawdust pellets of test species

	Sum of Square	df	Mean Square	F	Sig.
Between group	94.619	2	47.309	520.903	0.000
Within group	3.815	42	0.091		
Total	98.433	44			

Also, the ash content data obtained for *Intsia bijuga* (2.8%) and *Pometia piñata* (4.5%) were compared for the same species (Table 1) [37]. The results obtained for the species in this experiment were greater than the report [37] who recorded *I. bijuga* (1.4%) and *P. pinnata* (0.8%). This study suggested that variability in ash contents could be due to differences in the physical and chemical characteristics of test specimens (dimension/volume, density, and extractive contents).

3.6. Potentiality of the Test Species for Fuelwood

As per the results of this case study (Table 4), the heat calorific values generated by sawdust pellets (treatment) and solid woods (treatment) of the three species were lower than the standard heat energy requirement of 20.0 kJ/g [37]. On the other hand, the ash residues of the treatment specimens of the three species were comparatively low (Table 6). In this case, the three species were unsuitable for fuelwood and energy production as far as heat energy outputs of the treatment were concerned. However, the solid woods of *P. pinnata* indicated as a potential fuelwood candidate with an equivalent heat calorific value of 20.659 kJ/g meeting the requirement of fuelwood. As far as ash contents were concern, *I. bijuga* could likely contest for fuelwood potentiality as the ash remain was low (2.8%).

4. Conclusion and Recommendations

The combustion characteristics (heat energy outputs and ash contents) varied markedly between the sawdust pellets (treatment) and solid woods (control) of the three species (*Araucaria cunninghamii, Intsia bijuga* and *Pometia piñata*). Comparatively, the treatment specimens of *A. cunninghamii* generated higher heat calorific value than the control specimens. On the other hand, the treatment specimens of *I. bijuga* and *P. pinnata* yielded lower heat energies than their control specimens. In this case, the solid woods (control) of *I. bijuga* and *P. pinnata* produced higher heat energies than the sawdust pellets (treatment). According to the ash content analysis, high ash remains were observed for *A. cunninghamii* followed by *P. pinnata* and *I. bijuga*. As far as fuelwood potentiality was concerned, the treatment specimens of the three species could not meet the standard heat energy requirement (20.0 kJ/g) and therefore, were unsuitable as fuelwoods. Except for the control specimens of *P. pinnata* that produced an equivalent heat calorific value and thus, this species could hold a potential for fuelwood.

Despite the conditioning of test specimens of the three species to constant (unit) mass of 1.0 g, the heat energy outputs and ash contents differed due to the differences in specimen dimensions (treatment and control) which contributed to differences in volumes and oven dry densities. Additionally, this research suggested that other factors that affected combustion characteristics were physical and chemical properties of the test specimens as well as the use of hand-held pelletizing device for solidifying sawdust pellets.

For similar studies in future, this work recommends the use of test specimens (sawdust and solid wood) with uniform dimensions and mass (hence, uniform volume and density) for assessing the combustion characteristics. Also, the use of advance mechanized (standard) device for pelletizing sawdust particles for solidifying (densification) is highly desirable.

Author Contributions: Conceptualization, BKG; methodology, KAT; software, KAT; validation, BKG and KAT; investigation, KAT; data curation and formal analysis, BKG and KAT; writing-original draft, BKG; writing-review and editing, BKG; visualization, BKG; supervision, BKG; project administration, KAT; funding acquisition, KAT. All authors have read and agreed to the published version of the manuscript.

Funding: The research was funded by the Graduate Assistance Program, Postgraduate School of the PNG University of Technology, Lae, Papua New Guinea.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We acknowledge the following organizations and personnel of the PNG University of Technology: late Dr. Mex Peki, Professor Osea Gideon, and Mr. Leo Wana of the Forestry Department for their assistance towards completion of the research, Mrs. Elizabeth Matrus and Mr. Tata Telawicka of Analytical Laboratory for using the semi-automatic bomb calorimeter for combustion tests. Also, we thank Professor Barbara Ozarska from the University of Melbourne, Australia, for proof-reading and comments on the draft manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Bowyer, J.L.; Shmulsky, R.; Haygreen, J.G. *Forest Products & Wood Science. An introduction,* 5th ed; Blackwell Publishing: Iowa, USA, 2007, 1-558.
2. Miranda, R.C. de; Sepp, S.; Ceccon, E., Owen, M. Commercial woodfuel production. Experience from three locally controlled wood production models. ESMAP. The World Bank, 2012, 1-40. www.esmap.org
3. Nuberg, I.K. Developing the fuelwood economy of Papua New Guinea. *Energy Sustainable Dev.*, **2015**, 24, 9-18
4. Evans, J. *Tree planting for industrial, social, environmental, and agroforestry. Plantation forestry in the tropics*, 2nd ed; Oxford University Press: Oxford, USA, 1992, 1-403.
5. Forestry Economics and Policy Division; Forest Management Division. FAO of the United Nations. Global forest resources assessment 2005– progress towards sustainable forest management, FAO Forestry Paper, 2006. ISBN: 9251054819. https://www.fao.org/publications/card/en/c/4821656d-4806-5c6f-9a7d-ec5d702c29a6/

6. Lauri, P.; Havlik, P.; Kindermann, G.; Forsell, N.; Bottcher, H.; Obersteiner, M. Woody biomass energy potential in 2050. *Energy Policy*, **2013**, 1-13. DOI: http://dx.doi.org/10.1016/j.enpol.2013.11.033
7. World Energy Council (2017) World Energy Resources – Bioenergy. Available online: https://www.worldenergy.org/asserts/downloads/1.-World-Energy-Issue-Monitor-2017-Full-Report.pdf (accessed on 5 May 2018)
8. Sepp, S.; Sepp, C.; Mundhenk, M. Stocktaking paper on successful initiatives in developing countries in the field of wood energy development. Towards sustainable modern wood energy development. *GIZ*, Revised Version, 2014, 1-75.
9. World Energy Council (2016) World Energy Resources – Bioenergy. Available online: https://www.worldenergy.org/wpcontent/uploads/2017/03/WEResources_Bioenergy_2016.pdf (accessed on 1 May 2018)
10. The Outlook for Energy (2012) A view to 2040: A publication of Exxon Mobil. Available online: http://www.wecfrance.org/Documents PDF/rapports/RapportEXXONMOBIL.pdf (accessed on 18 June 2018)
11. Palash, S.M.; Kalam, M.A.; Masjuki, H.H.; Masum, B.M.; Fattah, I.M.R.; Mofijur, M. Impacts of biodiesel combustion on NOx emissions and their reduction approaches. *Renew. Sustain. Energy Rev.*, **2013**, 23, 473-490. DOI: 10.1016/j.rser.2013.03.003
12. Shahabuddin, M.; Liaquat, A.M.; Masjuki, H.H.; Kalam, A.M.; Mofijur, M. Ignition delay, combustion and emission characteristics of diesel engine fueled with biodiesel. *Renew. Sustain. Energy Rev.*, **2013**, 21, 623-632. DOI: 10.1016/j.rser.2013.01.019
13. Guo, M.; Song, W.; Buhain, J. Bioenergy and biofuels: history, status and perspectives. *Renew. Sustain. Energy Rev.*, **2015**, 42, 712-725.
14. Niju, S.; Balajii, M.; Anushya, C. A comprehensive review on biodiesel production using *Moringa oleifera* oil. *Int. J. Green Energy*, **2019,** 1-13. Taylor & Francis. DOI: https://doi.org/10.1080/15435075.2019.1619565
15. Ali, M.; Naqvi, B.; Watson, I.A. Possibility of converting indigenous *Salvadora persica* L. seed oil into biodiesel in Pakistan. *Int. J. Green Energy*, **2018,** 15, 427-435. DOI: 10.1080/15435075.2018.1472603
16. Gaworecki, M. South Korea subsidizing biomass so heavily that wind and solar are being crowded out of the market. News & Inspiration from Nature's Frontline, MONGABAY, 2020. Available online: https://news.mongabay.com/2020/04/south-korea-subsidizing-biomass-so-heavily-that-wind-and-solar-are-being-crowded-out-of-the-market/ (accessed on 5 October 2021)
17. Anon. Charcoal briquettes: A feasibility fuel option for Australia's fuel market, 2020. Available online: https://www.charcoalbriquettemachine.com/news/Australia-charcoal-briquettes-market.html (accessed 10 October 2021)
18. Lineback, N.; Dellinger, T.; Shienvold, L.F.; Witcher, B.; Reynolds, A.; Brown, L.E. Industrial greenhouse gas emissions: Does CO_2 from combustion of biomass residue for energy really matter? *Clim Res,* **1999**, 13, 221-229
19. Leturcq, P. Wood preservation (carbon sequestration) or wood burning (fossil-fuel substitution), which is better for mitigating climate change? *Ann. For. Sci.* **2014**, 71, 117-124. DOI: 10.1007/s13595-013-0269-9
20. Wang, L.; Dibdiakova, J. Characterization of ashes from different wood parts of Norway spruce tree. *Chemical Engineering Transactions,* **2014**, 37, 37-42. DOI: 10.3303/CET1437007
21. Boundy, B.; Diegel, S. W.; Wright, L.; Davis, S. C. Biomass energy data book: Edit. 4. Energy Efficiency & Renewable Energy, Oak Ridge National Laboratory: U.S. Department of Energy, 2011. DOI: http://cta.ornl.gov/bedb
22. IRENA. Reaching zero with renewables: Eliminating CO_2 emissions from industry and transport in line with the 1.5 ºC climate goal. International Renewable Energy Agency, Abu Dhabi, 2020, 1-214. Available online: www.Irena.org/publications (accessed 20 October 2021)
23. Yoshida, Y.; Dowaki, K.; Matsumura, Y.; Matsuhashi, R.; Li, D.; Ishitani, H.; Komiyama, H. Comprehensive comparison of efficiency and CO_2 emissions between biomass energy conversion technologies – position of supercritical water gasification in biomass technologies. *Biomass Bioenergy*, **2003**, 25, 257-272. DOI: 10.1016/S0961-9534(03)00016-3
24. Searchinger, T.D.; Hamburg, S.P.; Melillo, J.; Chameides, W.; Havlik, P.; Kammen, D.M.; Likens, G.E.; Lubowski, R.N.; Obersteiner, M.; Oppenheimer, M.; Robertson, G.P.; Schlesinger, W.H.; Tilman, G.D. Fixing a critical climate accounting error. *Science,* **2009**, 326, 527-528
25. Johnson, E. Goodbye to carbon neutral: getting biomass footprints right. *Environ. Impact Assess. Rev.*, **2009**, 29, 165-168
26. Cherubini, F.; Peters, G. P.; Berntsen, T.; Stromman, A. H.; Hertwich, E. CO_2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. *GCB Bioenergy*, **2011**, 3, 413-426. DOI: 10.1111/j.1757-1707.2011.01102.x
27. Catanoso, J. Scientists warn U.S. Congress against declaring biomass burning carbon neutral. News & Inspiration from Nature's Frontline. MONGABAY, 2020. Available online: https://news.mongabay.com/2020/05/scientists-warn-congress-against-declaring-biomass-burning-carbon-neutral/ (accessed 5 October 2021)
28. Fengel, D.; Wegener, G. *Wood: chemistry ultrastructure reactions*, 1st ed.; De Gruyter: Berlin, Germany, 1989, 1-613.
29. Fuwape, J.A. Effects of extractives on heating value of *Gmelina arborea*. *J. Trop. For. Sci.,* **1992**, 4, 281-285.
30. Walker, J.F.C. *Primary wood processing: principles and practices,* 1st ed.; Chapman & Hall: London, UK, 1993, 1-595.
31. Demirbas, A. Relationships between heating value and lignin, moisture, ash and extractive contents of biomass fuels. *Energy Explor. Exploit.*, **2002**, 20, 105-111
32. Hamaguchi, M.; Cardoso, M.; Vakkilainen, E. Alternative technologies for biofuel production in kraft pulp mills. Potential and Prospects. *Energies,* 2012, 5, 2288-2309. DOI: https://10.3390/en5072288
33. Menucelli, J.R.; Amorim, E.P.; Freitas, M.L.M.; Zanata, M.; Cambuim, J.; de Moraes, M.L.T.; Yamaji, F.M.; da Silver Jr, F.G.; Longui, E.L. Potential of *Hevea brasiliensis* clones, *Eucalyptus pellita* and *Eucalyptus tereticornis* wood as raw materials for bioenergy based in higher heating value. *Bioenergy Res.,* **2019**, 12, 992-999. DOI: https://doi.org/10.1007/s12155-019-10041-6
34. Tsoumis, G. *Science and technology of wood. Structure, properties, utilization*, 1st ed.; Chapman & Hall: London, UK, 1991, 1-595.

35. Desch, H.E.; Dinwoodie, J.M. *Timber: structure, properties, conversion and use*, 7th ed.; Macmillan Press LTD: London, UK, 1996, 1-306.
36. Wang, G.L.; Luo, Y.H.; Deng, D.; Kuang, J.H.; Zhang, Y.L. Pretreatment of biomass by torrefaction. *Chin. Sci. Bull.*, **2011**, 56, 1442-1448
37. Johnathan, M.; Saulei, S.; Marasinghe, B. A study on burning characteristics of some preferred fuel wood tree species in Papua New Guinea, 2016. Available online: https://www.researchgate.net/publication/268365264 (accessed 20 June 2018)
38. McKendry, P. Energy production from biomass (part 1): overview of biomass. *Bioresour. Technol.*, **2002**, 83, 37-46.
39. Szyszlak-Barglowicz, J.; Zajac, G.; Piekarski, W. Energy biomass characteristics of chosen plants. *Int. Agrophys*, **2012**, 26, 175-179. DOI: 10.2478/v10247-021-0025-7
40. Rao, G.R.; Reddy, N.N.; Srinivas, I.; Dixit, S. Potential of tree borne oil seeds (TBOs) for rural energy needs: experiences and implications. *Journal of Rural Development*, **2012**, 31, 335-345
41. Ranasinghe, S. Model fuelwood plantations for sustainable energy supply and livelihood development. Project on Promoting Sustainable Biomass Energy Production and Modern Bio-Energy Technologies – Sustainable Energy Authority, Ministry of Power & Renewable Energy. Joint Project of FAO and UNDP, Sri Lanka 2018, 1-20.
42. Post Courier. PNG biomass aims to make progress in 2019, 2019, 4-5.
43. Economics Consulting Services. Economic impacts of a biomass power project in Papua New Guinea, 2017. Available online: http://pngbiomass.com/wp-content/uploads/documents/PNG-Biomass-economic-impact-assessment.pdf (accessed on 13 September 2021)
44. Nuberg, I.K.; Mitir, J.A.; Robinson, B. Short-rotation coppice agroforestry for charcoal small business in Papua New Guinea. *Aust. For.*, **2017**, 80, 143-152. DOI: https://doi.org/10.1080/00049158.2017.1339238
45. Omer, A.M. Biomass energy resources utilization and waste management. *Agricultural Sciences*, **2012**, 3, 124-145. DOI: http://dx.doi.org/10.4236/as.2012.31016
46. Redman, A. and Fitzgerald, C. (2016) Enhancing value added wood processing in Papua New Guinea. Australian Centre of International Agricultural Research Project FST/2012/092.
47. Nunez, C.A.F.; Jochum, J.; Vargas, F.E.S. Characterization and feasibility of biomass fuel pellets made of Columbian timber, coconut and oil palm residues regarding European standards. *Environmental Biotechnology*, **2012**, 8, 67-76
48. Harun, N.F.; Afzal, M.T. Effect of particle size on mechanical properties pellets made from biomass blends. 4th International Conference on Process Engineering and Advanced Materials, *Procedia Eng.*, **2016**, 148, 93-99. DOI: 10.1016/j.proeng.2016.06.445
49. Gravalos, I.; Xyradakis, P.; Kateris, D.; Gialamas, T.; Bartzialis, D.; Giannoulis, K. An experimental determination of gross calorific value of different agroforestry species and bio based industry residues. *Natural Resources*, **2016**, 7, 57-68
50. Sukiran, M.A.; Abnisa, F.; Daud, W.M.A.W.; Bakar, N.A.; Loh, S.K. A review on torrefaction of oil palm wastes for biofuel production. *Energy Convers. Manage.*, **2017**, Available online: http://dx.doi.org/10.1016/j.enconman.2017.07.011 (accessed 15 July 2018)
51. Zaichenko, V.M.; Shterenberg, V. Ya. Torrefaction of wood pellets: New Solutions. Energy Saving, New and Renewable Energy Sources. *Therm. Eng.*, **2017**, 64, 729-737. DOI: 10.1134/S0040601517100111
52. Artemio, C.P.; Maginot, N.H.; Serafin, C.U.; Rahim, F.P.; Guadalupe, R.P.J.; Fermin, C.M. Physical, mechanical and energy characterization of wood pellets obtained from three tropical species. *PeerJ6:e5504*, **2018**, DOI: 10.7717/peerj.5504 Available online: https://www.researchgate.net/publication/327418815 (accessed on 14 June 2018)
53. Ramos-Carmona, S.; Martinez, J.D.; Perez, J.F. Torrefaction of patula pine under air conditions: A chemical and structural characterization. *Ind. Crops Prod.*, **2018**, Available online: https://doi.org/10.1016/j.indcrop.2018.03.062 (accessed on 30 May 2018)
54. Romao, E.L.; Conte, R.A. Energy gains of *Eucalyptus* by torrefaction process. *Maderas-Cienc Tecnol.*, **2021**, 23, 1-6. DOI: 10.4067/s0718-221x2021000100403
55. Ness, J.; Moghtaderi, B. Chapter 1: Biomass and bioenergy, Coal-Biomass Cofiring Handbook, 2007, 1-36. Available online: https://www.researchgate.net/publication/309127353 (accessed on 12 June 2020)
56. Pessoa-Jr, A.; Roberto, I.C.; Menossi, M.; dos Santos, R.R.; Filho, S.O.; Penna, C.T.V. Perspectives on bioenergy and biotechnology in Brazil. *Appl. Biochem. Biotechnol.*, **2005**, 121, 57-70. DOI: https://doi,org/10.1385/ABAB:121:1-3:0059
57. Scott, P.T.; Pregelj, L.; Chen, N.; Hadler, J.S.; Djordjevic, M.A.; Gresshoff, P.M. *Pongamia pinnata*: An untapped resources for the biofuels industry of the future. *Bioenerg. Res.*, **2008**, 1, 2-11. DOI 10.1007/s12155-008-9003-0
58. Gusamo, B.K.; Jimbudo, M. Tree-borne oil seed crops: *Jatropha curcus*, *Rhicinus communis*, and *Anacardium occidentale* and their potential for bio-energy source in Papua New Guinea. *J. Agric. Environ. Sci.*, **2015**, 4, 113-123. DOI: 10.15640/jaes.v4n2a13
59. Krishnakumar, J.; Venkatachalapathy, V.S.K.; Elancheliyan, S. Technical aspect of biodiesel production from vegetable oils. *Thermal Science*, **2008**, 12, 159-169. DOI: 10.2298/TSCI0802159K
60. Chakravarty, S.; Suresh, C. P.; Shukla, G. Tree-borne oilseeds. *Environment & Ecology*, **2010**, 28, 1520-1524. DOI: https://www.researchgate.net/publication/280952838
61. Romano, S.D.; Sorichettii, P.A. Dielectric spectroscopy in biodiesel production and characterization. Green Energy and Technology. Springer-Verlag, London, UK, 2011, 1-103. DOI: https://10.1007/978-1-84996-519-4_2
62. Ahmia, A.C.; Danane, F.; Bessah, R.; Boumesbah, I. Raw material for biodiesel production. Volarization of used edible oil. *Revue des Energies Renouvelables,* **2014**, 17, 335-343.
63. Gashaw, A.; Lakachew, A. Production of biodiesel from non-edible oil and its properties. *International Journal of Science, Environment and Technology*, **2014**, 3, 1544-1562. www.ijset.net

64. Dhyani, S.K.; Vimla Devi, S.; Handa, A.K. Tree borne oil seeds for oil and biofuel. Technical Bulletin 2/2015. ICAR-CAFRI, Jhansi, India, 2015, 1-50.
65. Arentz, F.; Keating, W.G.; Ilic, J. (1994) Araucaria A.L. Juss. In *Timber trees: Major commercial timbers;* Soerianegara, I., Lemmens, R.H.M.J., Eds.; Plant Resources of South-East Asia, Pudoc Scientific Publishers: Wageningen, The Netherlands, 1994, 5, 108-114.
66. Eddowes, P.J. *Commercial timbers of Papua New Guinea,* 1st ed.; Department of Forest: Port Moresby, Papua New Guinea, 1977, 1-195.
67. Pillotti, C.A. The chemistry and durability of PNG timbers. In Proceedings of the Forest Products Research Seminar 26-27 October 1992;JICA-FRI Publications: Research Note No.7, pp. 57-61.
68. ASTM. 1972. Standard Method of Preparing Coal Samples For Analysis. ASTM D2013-72. Annual Book for ASTM Standards: Philadelphia, PA, USA. Available online: https://www.epa.gov/sites/default/files/2020-11/documents/app-c2.pdf (accessed on 11 March 2018)
69. ASTM. 2013. Standard test method for gross calorific value of coal and coke. ASTM D5865-13. ASTM International. West Conshohocken, PA, USA. Available online: www.astm.org (accessed on 11 March 2018)
70. ASTM. 1984. Standard test method for ash in wood and wood based materials. ASTM D1102-84. ASTM International. West Conshohocken, PA, USA. Available online: www.astm.org (accessed on 11 March 2018)
71. Chandrasekaran, S. R.; Hopke, P. K.; Rector, L.; Allen, G.; Lin, L. Chemical composition of wood chips and wood pellets. *Energy Fuels,* **2012**, 26: 4932-4937. DOI: 10.1021/ef300884k
72. Kamperidou, V.; Lykidis, C.; Barmpoutis, P. Thermal characteristics of wood of some common native species. Implementation of Wood Science in Woodworking Sector. 27th International Conference on Wood Modification and Technology 2016, 2016, 115-122
73. Stahl, M. Improving wood fuel pellets for household use – perspectives on quality efficiency and environment. Ph.D, Karlstads University, Sweden, 2008.