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A Comparative Evaluation of Combustion Characteristics of *Araucaria cunninghamii*, *Intsia bijuga* and *Pometia pinnata* for Bio-Energy Source

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Abstract: Burning woody biomass for energy is gaining attention due to the environmental issues associated with fossil fuels and carbon emissions. The carbon released from burning wood is absorbed by plants and, hence, offsets pollution. 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* to 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 a cylindrical dimension (volume 1178.57 mm^3, oven-dry density 0.0008 g/mm^3). Meanwhile, 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 a temperature of 105 °C) 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 the test specimens of the three species. Comparatively, the treatment specimens of *A. cunninghamii* produced a 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, respectively) 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 an 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; bio-energy; Papua New Guinea

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1. Introduction

Burning wood as an energy source, for heating, cooking, lighting, and 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% of the population of Papua New Guinea (PNG) depends on fuelwood [3]. About 90% of fuelwood is used in tropical countries [4], while a 60 to 80% share of wood consumption is fuelwood in the developing world [2]. Furthermore, about 53% of wood was consumed worldwide for energy over the past 17 years [5]. A recent report [6] highlights that 21% of energy consumption was derived from renewable sources in 2020 in the U.S. Globally, the total energy generation from renewable sources (biomass) increased in 2020 (7%) and 2021 (8.3%) [7]. In addition, another article [8] reported a 9.7% rise in renewable energy (including biofuels) worldwide in 2020. It is projected that 18% of the world's energy consumption will be sourced from wood by 2050 [9]. Moreover, more than half the world's population relies on forest biomass for energy [10]. Furthermore, a population of 2.7 billion will rely on biomass energy by 2030 [11]. 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% [12]. However, the issue with burning fossil fuels for energy is that it 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' [13–15]. The focus is on renewable energy, and forest biomass is identified as a potential bio-energy source [16]. Biomass, the fourth largest contributor of bio-energy [12], has the advantages of being renewable and sustainable, abundantly available, and environmentally benign [17]. Furthermore, biomass has low embodied energy and is cost effective [1], technically feasible, and economically viable [18]. Currently, the industrial bio-energy market is increasing in Europe and the U.S., and Eastern Europe biomass industries are manufacturing millions of tons of wood pellets to supply the market [19]. Additionally, South Korea is subsidizing forest biomass for renewable energy [19]. Meanwhile, Australia intends to supply the European energy market with 15,000 tons of charcoal briquettes made from eucalyptus [20]. In PNG, industrial conversion of forest biomass into energy products is non-existent although there is a potential to utilize the vast forest resource and tap into international renewable energy markets. As far as GHG is concerned, biomass combustion releases carbon which has a similar effect as carbon emitted from fossil fuels [21,22]. Comparatively, the carbon released from burning biomass is lower than fossil fuels [23,24]. For example, burning 1.0 t of biomass generates 1.5 t of CO_2, on average [18]. Furthermore, IRENA [25] reported that 36.9 Gt of CO_2 was released in 2017. Additionally, Yoshida et al. [26] compared the CO_2 emitted from burning biomass with conventional fuels, such as biomass (10 g C MJ^{-1}), gasoline (150 g C MJ^{-1}), and diesel (140 g C MJ^{-1}). Moreover, bio-energy advocators assert that carbon emission from biomass combustion is absorbed by growing trees and the process is 'carbon neutral' with zero-net carbon emission [22]. However, many environmental scientists argue that the carbon neutrality concept is erroneous, misleading, and could destabilize the climate [22,27–30].

Combustion characteristics vary significantly within and between timber species. These are attributed to the 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 [31–35]. In addition, high density woods with long fibers and thick cell walls, low holocellulose, and high extractive and lignin contents, have high heating values and, thus, are potential materials for bioenergy [36]. Comparatively, resinous softwoods yield higher heating values than hardwoods [33,37,38]. Furthermore, wood's hygroscopic nature, moisture content, temperature, and structural features influence combustion and flammability [37,39]. After the combustion of biomass, the remains are ash content. Ash content, the mass of the biomass material that remains after high temperature burning in the presence of oxygen, is expressed as a percentage of the moisture-free weight of the wood [1]. It is expressed that ash content is an important parameter that determines calorific value [40]. High ash content reduces the effect of fuel quality and affects the efficiency of the combustion process. Furthermore, the properties of biomass to consider during the processing of energy are calorific value, proportions of carbon and volatiles, ash content, alkali metal content, and cellulose/lignin ratio [41].

Globally, combustion characteristics of various forest species are studied extensively for their fuelwood potential. For the categorizing of a species for its potentiality as fuelwood, Johnathan et al. [40] stated a 20.0 kJ/g heat calorific value as a standard. The authors [40] reported 21.7 kJ/g (as average heating values) for 31 PNG species, and recommended potential fuelwoods. In addition, species with fuelwood potentials have been selectively cultivated in woodlots and plantations to provide feedstocks for the biofuel industry around the world. For instance, in Poland, three species are managed on a short rotation plantation for bio-energy [42]. Brazil has the world's largest Eucalyptus plantation devoted to bio-energy [11]; India launched 600,000 ha of biofuel plantations on wastelands from 2004–2005 [43]; and in Sri Lanka, a plantation (101.6 ha) was tried with 12 different species for fuelwood [44]. Meanwhile, in PNG, a bio-energy project has established a 2400 ha plantation (as of 2018) of *Eucalyptus pellita* and *Acacia* spp. for electricity generation [45] and is anticipated to secure 22,000 ha on a long-term basis [46]. Additionally, small business opportunities were identified in charcoal production from short-rotation agroforestry practices in PNG [47].

Technologies are available to convert biomass residues/wastes from primary industries for biofuel products [48]. Agroforestry residues include shavings, slabs, sawdust, and off-cuts from forest industries [49]. Meanwhile, rice and wheat husks, kernels, and palm oil wastes from agricultural industries [50–53] are prime raw materials for biofuels. These feedstocks are converted into biofuel products (charcoal, briquettes, pellets, and biogas) using modern technological processes, e.g., combustion, carbonization, pyrolysis, gasification, fermentation, biochemical, and transesterification [34,54]. Prior to their conversion into biofuels, pre-treatments (defiberization, densification, pelletizing, and torrefaction) are carried out to improve biomass characteristics and, hence, increase heat energy output [34,54]. In this case, solid materials are reduced to fine particles, dried, solidified into pellets, and torrified [54–57]. Furthermore, advanced technologies are adopted for the production of biofuel liquids on industrial scales, e.g., the fermentation of sugarcane wastes for bioethanol [58]. Globally, Brazil is the largest bioethanol producer after the U.S. [59]. Additionally, vegetable oils derived from plant seed kernels [60,61] are converted into biodiesel through transesterification for energy source [62–67].

This case study examines the combustion characteristics of a plantation-grown *Araucaria cunninghamii* Ait., and the natural hardwoods *Intsia bijuga* Kuntze. and *Pometia pinnata* Forst. The specific objectives were to:

- make a comparative assessment of the heat energy outputs between the sawdust pellets and solid woods, and analyze the ash contents of the sawdust pellets.
- make recommendations on the potential of the species for fuelwood.

The three test species selected for the combustion experiment were based on their commercial importance and local end uses. Presently, the state (PNG Forest Authority) manages 12,000 ha of *Araucaria cunninghamii* plantation that provides an important feedstock for the plywood-making industry. Alternatively, *Intsia bijuga* and *Pometia pinnata* are valuable species found in lowland forest and are sought by processing industries (sawmills) for sawn timber production. The sawn boards are then seasoned and processed for decorative and structural constructions. In many rural communities of PNG, these species are extracted and utilized for traditional constructions as well as fuelwood for energy.

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. cunninghamiii* (Araucariaceae family) is a coniferous tree and has a low-to-medium weight and hardness [68]. The other two species are hardwoods. *I. bijuga* (Fabaceae family) has hard and heavy wood, while *P. pinnata* (Sapindaceae family) has a medium weight and hardness [69]. Wood density, chemical analysis, and the combustion characteristics of the species, based on PNG-grown materials, are shown in Table 1.

Table 1. Physical and chemical properties of test species.

Test Species	Physical Property †	Chemical Analysis (%) **	Combustion/Energy Values ‡	
	Density (kg/m^3) *	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 [69]; ** Pillotti [70]; and ‡ Johnathan et al. [40]. * Density at 12% moisture content. AC is the ash content and HCV is the heat calorific value. Note: the chemical and combustion properties of *A. cunninghamii* are unknown to date.

The three test species were sourced from the Bulolo plantation (*Araucaria cunninghamii*) and Wafi natural forest (*Intsia bijuga* and *Pometia pinnata*) of the Morobe Province, PNG. The log of *A. cunninghamii* was brought to PNG Forest Products Ltd, Bulolo, while *I. bijuga* and *P. pinnata* logs were taken to Lae Builders and Contractors Ltd, Lae, for processing into lumber. The two sawmills were selected for processing the logs based on their close proximities to the forest sites from which the logs were extracted. After processing, a 1.0 m sawn board and 10 kg of sawdust of each species (i.e., three pieces of 1.0 m sawn boards and three 10.0 kg of sawdust) were collected from the sawmills. The sawn boards and sawdust were selectively obtained from heartwood portions of the logs. The sawn boards and sawdust samples were placed in plastic bags and taken to the analytical science laboratory of the Department of Agriculture, PNG University of Technology, Lae. The test materials were stored in the laboratory where conditions (temperature and relative humidity) were controlled in order to avoid infection 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 °C, and dried to 14% moisture content (MC) following the procedure used by Jonathan et al. [40]. 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). All specimens were then returned to the oven drier for further conditioning to constant weights (1.0 g). The total number of specimens, and their replicates, of solid wood (control) per species are shown in Table 2, and the physical characteristics (mass, volume, oven-dry density) for the control specimens are provided in Table 3.

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

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

Test Specimens	Mass (g)	Volume (mm^3)	Density (g/mm^3)
Solid woods *	1.0	1000.00	0.001
Sawdust pellets **	1.0	1178.57	0.0008

* control, ** treatment.

2.2.2. Preparation of Sawdust Particles: Sieving and Pelletizing

Following the ASTM D2013-72 standard [71] (with some modifications), the sawdust particles of the three species were sieved by passing them through a 250 μm sieving tray. The fine particles were collected, placed in an oven drier at a temperature of 105 °C, and conditioned to 14% MC. The MC of the fine sawdust particles was computed (Equation (1)):

$$MC = \frac{M2 - M3}{M2 - M1} \times 100 \quad (1)$$

where MC is the moisture content (%), M1 is the mass of the weighing dish and lid (g), M2 is the mass of the weighing dish and lid plus the sawdust before drying (g), and M3 is the mass of weighing dish and lid plus the sawdust after drying (g).

After conditioning, the fine particles were composed and compacted following Harun and Afzal's method [51]. 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 poured into a steel cylinder (height 15 cm and diameter 1 cm) of the pelletizer and lightly pressed with hands. In the pelletizer, the steel cylinder containing the fine particles was tightened with a screw-like knob until it was tight enough to compact and solidify the particles. The resultant products were highly densified sawdust pellets of cylindrical dimensions (Figure 1). The total number of sawdust pellets (treatment), including the replicates, are shown in Table 2, and the physical characteristics (mass, volume, oven-dry density) for the treatment specimens are shown in Table 3.

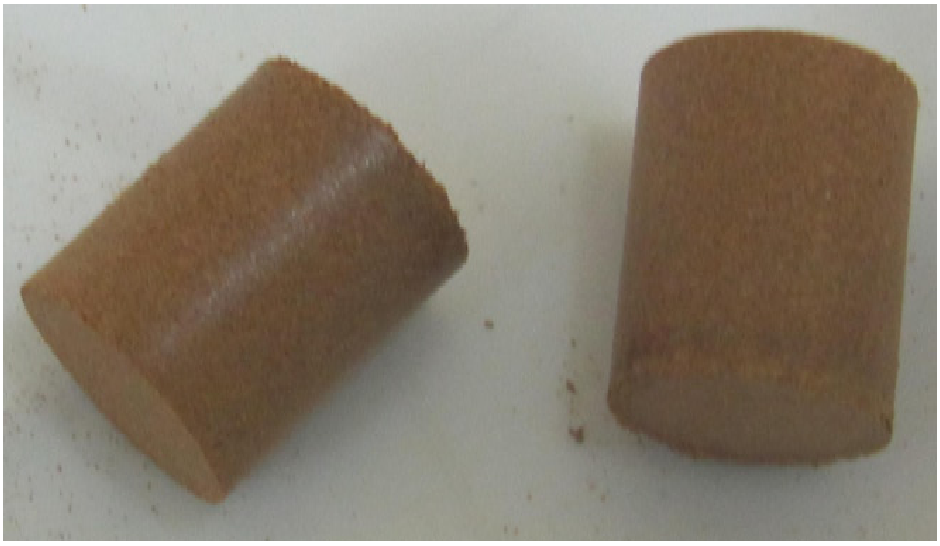

Figure 1. Densified sawdust pellets.

The density of the pellets was calculated (Equation (2)) from the mass divided by volume, as per Artemio et al. [55]:

$$D = \frac{M}{V} \quad (2)$$

where D is the pellet density (g/mm^3), M is the mass of the pellet (g), and V is the volume of the pellet (mm^3).

2.2.3. Experimental Design

The design of the experiment was based on complete randomized design. In this experiment, sawdust pellets were used as the treatment while the solid wood cubes were the control as outlined 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. [40].

An individual specimen of the treatment and control (1.0 g) specimens was placed in a crucible to the bomb electrodes. The specimen was tied to an ignition rope with both ends tied to the ignition wire (6 cm length) whilst the bomb head was on its support. The ends of the ignition wire were attached to the electrodes to facilitate complete specimen combustion. Using a syringe, 1 mL of distilled water was squeezed into the bomb cylinder before the bomb was lowered and tightly closed to avoid leakage of the oxygen. The oxygen was allowed to flow into the combustion cylinder. After that, the combustion cylinder was lowered into a calorimeter bucket filled with 2100 mL of distilled water. In the head of the 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 the firing of the bomb using the ignition switch. It took approximately 5 min 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, the heat calorific value (kJ/g) was calculated (Equation (3)) as per the ASTM D5865-13 standard [72]:

$$\mathrm{GCV} = \frac{\mathrm{We}\Delta\mathrm{T} - (\mathrm{W1}(4.18) + \mathrm{W2}(0.335))}{\mathrm{M}} \tag{3}$$

where GCV is the gross calorific value (kJ/g), M is the mass of the specimen (g), We is the water equivalent (ml), W1 is the weight of the cotton thread (g), W2 is the weight of the fuse wire (g), and ΔT is the rise in temperature (°C).

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 °C) 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 [73] and the procedure applied by Chandrasekaran et al. [74], the sawdust pellets were placed in a porcelain crucible, using a muffle furnace, for 2 h at a temperature of 580 °C. 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 (4)) in accordance with Kamperidou et al. [75]:

$$\mathrm{AC} = \frac{\mathrm{M3} - \mathrm{M1}}{\mathrm{M2} - \mathrm{M1}} \times 100 \tag{4}$$

where AC is the ash content (%), M1 is the mass of the empty crucible (g), M2 is the mass of the crucible plus the test specimen (g), and M3 is the mass of the crucible plus ash.

2.3. Statistical Analysis of Data

The heat calorific value (kJ/g) generated by the individual specimen of the treatment and control specimens was compiled as raw data using an excel spreadsheet. The raw data was statistically analyzed, using the Special Package for the Social Sciences (SPSS) Version 16.0, for their minimum, maximum, mean, and standard deviations (Table 4). Furthermore, a boxplot analysis was generated to display the spread of heat calorific values (range, median, quartiles, and interquartile range) of treatment and control specimens of the test species (Figure 2) using the SPSS Version 16.0. Additionally, a one-way analysis of variance (ANOVA) was performed to test any significant variations (at 5% significance level) in the mean calorific values between the treatment and control specimens for the test species (Table 5). Moreover, the remains (ash contents) of the test species were statistically analyzed and presented (Tables 6 and 7).

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.

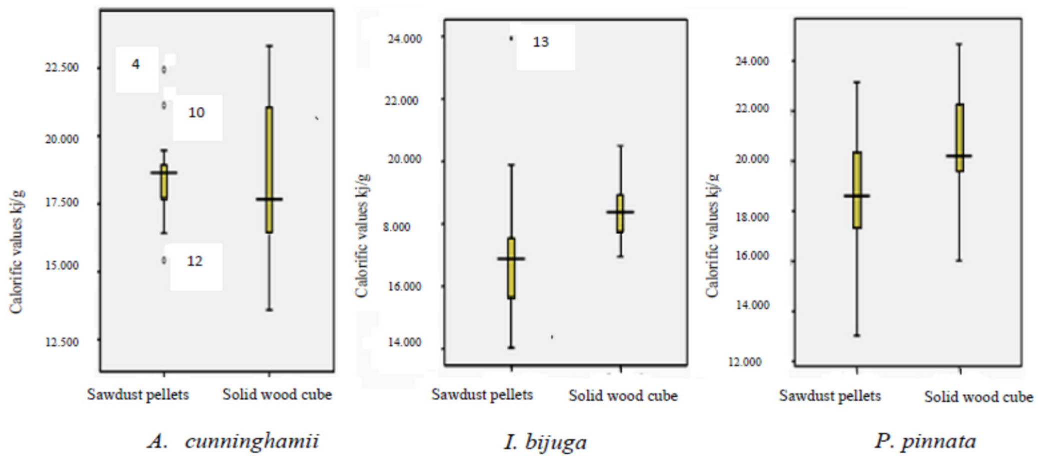

Figure 2. Boxplot analysis of heat energy output of treatment and control specimens of test species.

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

	Sum of Square	df	Mean Square	F	Sig.
A. cunninghamii					
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			

Table 6. Ash content analysis of ash content 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.

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			

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 specimens, 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 [37]. 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 [37].

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

A comparison was made for the 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), a higher mean calorific value was recorded for sawdust pellets (18.546 kJ/g) than the solid woods (18.376 kJ/g) in *Araucaria cunninghamii*. Lower mean calorific values were observed for the sawdust pellets of *Pometia pinnata* and *Intsia bijuga* (18.822 kJ/g and 17.124 kJ/g, respectively) compared with 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*.

According to Table 5, the ANOVA test (p = 0.05) revealed a significant difference (p < 0.038) in 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).

In addition, the minimum and maximum heat energy outputs of 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 then *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 the solid woods (control), the 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).

Furthermore, a boxplot analysis (Figure 2) was conducted to demonstrate the spread of medians and ranges of the sawdust pellets (treatment) and solid woods (control) of the test species. Accordingly, the median and range of *P. pinnata* (treatment and control) exhibited a wider spread than the *A. cunninghamii* and *I. bijuga*. Comparatively, *A. cunninghamii* had a wider spread (range and interquartile range) for solid woods, followed by *P. pinnata* and *I. bijuga*.

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

The heat energy outputs of the sawdust pellets (treatment) and solid woods (control) varied markedly although the test specimens were weighed to a constant (unit) mass of 1.0 g. The major contributing factors in 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 the oven-dry density (0.0002 g/mm^3) between the treatment and control specimens had an effect on the heat energy outputs. For instance, the high heat energy output in sawdust pellets of *A. cunninghamii* (18.546 kJ/g) was attributed to the high specimen volume, oven-dry density, pelletizing (densification), as well as resin contents. This observation correlated with the studies of Demirbas [34] and Stahl [76] who reported high heat energies from high density woods and solidification of particles.

After that, 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, respectively), despite high oven-dry densities, compared with 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 [32,34,40]. In addition, the lower heat energies that were observed for the sawdust pellets of *I. bijuga* and *P. pinnata* could be due to the use of immature heartwood and sapwood particles in the sawdust mixtures; a loss of volatile (extraneous) substances during log processing; storage, drying, and pelletizing processes; and the use of a hand-held mechanical device for the 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* in this study were compared with the published data (Table 1) [40]. As per the results (Table 4), heat energy outputs exhibited for sawdust pellets and solid woods of *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. [40] 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 the specimen dimensions used in this study compared with Johnathan et al. [40]. For instance, Johnathan et al. [40] applied large specimens (15 mm × 15 mm × 20 mm), while this study used cuboids (10 mm × 10 mm × 10 mm) for combustion. In addition, this study suggests that parameters (specimen age, moisture content, biochemical properties, and application of different 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%).

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 values (18.546 kJ/g and 18.822 kJ/g, respectively) compared to *I. bijuga* (2.8%) which had the heat calorific value of 17.124 kJ/g. The findings disagreed with many studies [32,34,40] that claim that the lower the ash residues, the higher the heat energy values. Additionally, an ANOVA test (p = 0.05) revealed a significant difference ($p < 0.00$) in the ash contents of the three species combusted in the experiment.

Furthermore, the ash content data obtained for *Intsia bijuga* (2.8%) and *Pometia piñata* (4.5%) were compared with the same species in Table 1 [37]. The results obtained for the species in this experiment were greater than the findings of Johnathan et al. [40] who recorded the ash remains as 1.4% and 0.8% for *I. bijuga* and *P. pinnata*, respectively. This study suggests that variability in ash contents could be due to differences in the physical (dimension/volume and density) and chemical (extractive contents) characteristics of the test specimens. Moreover, the use of a hand-held pelletizing device for the compaction and solidification of the sawdust pellets, as well as the level of experience of the person handling the device, contributed to differences in the ash contents generated.

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 the sawdust pellets (treatment) and solid woods (treatment) of the three species were lower than the standard heat energy requirement of 20.0 kJ/g [40]. 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 group were concerned. However, the solid woods of *P. pinnata* indicated that this is a potential fuelwood candidate, with its equivalent heat calorific value of 20.659 kJ/g meeting the requirement of fuelwood. As far the ash contents were concerned, *I. bijuga* could likely contest for fuelwood potentiality as the ash remain was low (2.8%).

4. Conclusions and Recommendations

The combustion characteristics, in terms of heat energy outputs and ash contents, varied markedly between the sawdust pellets (treatment) and solid woods (control) of the three test species (*Araucaria cunninghamii*, *Intsia bijuga*, and *Pometia piñata*). Comparatively, the treatment specimens of *A. cunninghamii* generated a 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*. The variations in combustion characteristics were attributed to physical (specimen dimensions, volumes, and oven-dry densities) and chemical (extractives) properties, as well as the hand-held pelletizing device used for solidifying the test specimens.

As far as fuelwood potentiality is 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. An exception was the control specimens of *P. pinnata* that produced an equivalent heat calorific value and, thus, this species could hold potential for fuelwood.

For similar studies that include other native species in future, this work recommends the use of test specimens (sawdust and solid wood) with uniform dimensions and mass (uniform volume and density), for assessing the combustion characteristics. In addition, the use of an advanced mechanized (standard) device, for pelletizing the sawdust particles for solidifying (densification), is highly desirable.

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