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Fast-growing native tree species to the secondary forest of East Kalimantan, Indonesia: Physicochemical properties of woody materials for bioelectricity feedstocks

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Abstract. *Yuliansyah. Haqiqi MT, Setiawan KA, Setiawan A, Saputra PD, Romadlon HSI, Mukhdlor A, Ramadhan R, Amirta R. 2022. Fast-growing native tree species to the secondary forest of East Kalimantan, Indonesia: Physicochemical properties of woody materials for bioelectricity feedstocks. Biodiversitas 23: 3379-3386.* The conversion of woody biomass into electricity through a thermochemical process has recently attracted significant attention worldwide to promote green energy production. It provides a low-cost and straightforward operation promising for developing rural areas, especially with limited transportation access. In East Kalimantan Province, almost all remote areas are surrounded by forests with high tree species diversity, which is the potential to be utilized for sustainable feedstocks in electric power plants. This study pointed out the energy potential produced from woody biomass of selected fast-growing tree species native to East Kalimantan secondary tropical forest: *Elaeocarpus ferrugineus* (Jacq.) Steud., *Ficus aurata* (Miq.) Miq., *Fordia splendidissima* (Blume ex Miq.) Buijsen, *Lindera lucida* (Blume) Boerl., *Mallotus paniculatus* (Lam.) Mull. Arg. and *Schima wallichii* (DC). Their wood physicochemical properties were firstly investigated. Furthermore, each species' wood quality for solid energy purposes was presented as the fuel value index (FVI). The results revealed that the change from greenwood into wood chip effectively removed the moisture content, thus improving efficiency to achieve higher energy potency. Our findings showed that the highest energy potency was obtained from the wood chip of *F. splendidissima* (3.61 MWh/ton), followed by *S. wallichii* (2.98 MWh/ton). A similar pattern was also found in FVI determination showing that the wood chip of *S. Splendidissima* had the greatest value (8970). Therefore, we observed that the high quality of *S. splendidissima* compared to other selected fast-growing species indicates its high suitability for further large-scale crop plantation to supply wood chips for biomass-based electricity generation.

Keywords: Electricity, fast-growing, native species, secondary forest, woody biomass

INTRODUCTION

The exploitation of fossil fuels has significantly increased the degradation of natural resources and the environment. Its combustion corresponding to generating electricity constantly accelerates the global warming potential. According to the report from the International Energy Agency, energy production from fossil fuels sectors is responsible for more than 80% of released carbon dioxide (CO_2) in the atmosphere, or it is estimated to exceed two-thirds of total greenhouse gas (GHC) emission (Ram et al. 2018; Cardoso et al. 2019). Although the Paris Agreement in 2015 implicitly called for shifting away from the domination of fossil fuels, the human population and industrialization are continuously growing, creating a significant challenge on how to mitigate climate change and reduce those harmful GHC effects (Karmaker et al. 2020; Rempel and Gupta 2020). The United Nations (UN), through the Climate Action Summit in New York in 2019, has set a global plan to achieve net-zero emissions by 2050 (Mutezo and Mulopo 2021). Therefore, many countries have committed to addressing a transition from fossil fuels to renewable energy by implementing a legal policy (Mola-Yudego et al. 2017; Moya et al. 2019; Rincon et al. 2019).

The usage of renewable energy has gained a lot of attention (Nugraha et al. 2020). Among all resources, biomass has been considered the most applicated renewable energy globally, with a proportion of 12.4% of the total energy consumption (Wang et al. 2020). Energy production from biomass is expected to meet global energy demands in the future (Bilgili et al. 2017). It offers various advantages over other renewable sources, such as better energy properties and less CO_2 emission (Liu et al. 2014; Tenorio et al. 2015). Woody biomass harvested from the forest is also one of the promising feedstocks to produce clean energy because it contains quite low sulfur and nitrogen (Hupa et al. 2017; Lee et al. 2021). Since almost all remote areas in Indonesia are covered by forests with limited transportation access, the approach to using its biomass will be adequate to overcome the electricity limitation in those rural areas. Moreover, it will improve economic growth by providing micro or small-scale electricity with a simple and cheaper process. When the wood is burned during the combustion stage, the CO_2 emission can be easily absorbed by available forest plant species through photosynthesis. The net cycle of CO_2 is always in balance, and this phenomenon is known as neutral carbon (Mäkipää et al. 2015; Proto et al. 2021). It will potentially lead to a zero-emission power system (Mori et al. 2022). Excellent performance of biomass-based electricity has been reported earlier (González et al. 2015). Furthermore, it has also been successfully developed in many countries in the world, such as in Brazil (Ferreira 2018), Finland (Majava et al. 2022), Ghana (Präger et al. 2019), India (Narnaware and Panwar 2022), Japan (Battuvshin et al. 2020), Portugal (da Costa et al. 2020), Spain (Aguado et al. 2022), and United States (Broughel 2019).

East Kalimantan province was one of Indonesia's most considerable bioenergy potentials due to its high availability of wood biomass resources from the forest (Simangunsong et al. 2017). The high diversity of biomass plant species distributed in the tropical rain forest of East Kalimantan was also reported as the essential biodiversity value in Indonesia for many endemic species compared to other places on the earth (Pio and D'Cruz 2005). However, the wood harvested from its forest resources was still dominated by the Dipterocarpaceae family, commonly used for furniture and construction purposes. Although it had promising calorific values, it was considered a low-growing tree species that was not desirable for sustainable energy crops (Yuliansyah et al. 2016). On the other hand, fast-growing tree species planted on forest plantations, such as *Acacia mangium*, *Anthocephalus cadamba*, *Eucalyptus pellita*, *Gmelina arborea*, and *Paraserianthes falcataria*, are have been reported to possess low heating value (Amirta et al. 2016; Haqiqi et al. 2022). Therefore, finding suitable plant species having high wood calorific value combined with their fast-growing ability to obtain high biomass yield for energy-electricity production is recently growing (Haqiqi et al. 2018).

The investigation of native species can be an important step in searching for suitable plant biomass species to be cultivated as energy crops in some remote areas. In East Kalimantan Province, many local fast-growing species are characterized as non-commercial species, even known as species with high adaptability to grow well in their origin ecosystem. They are mainly found in plant communities at secondary forest succession. Commonly used as firewood by local people, those species still have less attention for further large-scale utilization, especially in energy production. These species will promise future plantation of short-rotation wood crops to provide sustainable raw materials with a faster-growing ability. However, further wood physicochemical analysis was necessary to meet an ideal energy crop requirement. This study reported comparing wood physicochemical properties of selected fast-growing tree species native to the East Kalimantan forest to be used as feedstocks in electricity production.

MATERIALS AND METHODS

Study area

Wood biomass materials and leaf samples from some fast-growing native species were collected at the secondary forest of Mulawarman University Educational Forest (KHDTK Fahutan UNMUL, Samarinda), Samarinda City, East Kalimantan Province, Indonesia (0°25'10"S-0°25'10" S and, 117°14'00"E-117°14'14"E, 300 ha).

Biomass plant species

Medium trees with 6-8 cm diameter recognized as native fast-growing species naturally grown on secondary tropical rain forests in East Kalimantan were pointed out. Identification through leaf herbarium specimens of each species was deposited at the Laboratory of Forest Dendrology and Ecology, Faculty of Forestry, Mulawarman University, Samarinda, Indonesia. In this study, six species were identified, namely *Elaeocarpus ferrugineus* (Jacq.) Steud., *Ficus aurata* (Miq.) Miq., *Fordia splendidissima* (Blume ex Miq.) Buijsen, *Lindera lucida* (Blume) Boerl., *Mallotus paniculatus* (Lam.) Mull.Arg. and *Schima wallichii* (DC). They belong to different family groups, including Elaeocarpaceae, Moraceae, Fabaceae, Lauraceae, Euphorbiaceae and Theaceae, respectively. All woody biomass samples were collected in September 2021. They were debarked to analyze the dry bark-wood ratio, then converted into wood chips before proceeding to laboratory analysis.

Determination of wood physicochemical properties and energy potency

The total moisture and proximate compositions of wood materials were carried out according to ASTM D 7582-12 method. The lost weight of the samples after reaching the constant weight in a hot air oven at 105°C was calculated to determine the moisture content. For proximate analysis, the samples were dried and grounded into smaller sizes (±60 mesh). The measurements consisted of two steps in a furnace. The first step was done by heating from 300-575°C for 3 hours. The weight loss was measured and noted as a volatile matter (VM) substance. Then, the temperature was increased to reach 950°C for 2 hours to heat the remaining samples. After cooling down to room temperature, the residual weight was measured in ash content while the lost weight was fixed carbon (FC).

The ultimate compositions of wood biomass including carbon (C), hydrogen (H), and oxygen (O) were estimated based on the following Equation (Parikh et al. 2007):

$$C\ (\%) = (0.637 \times FC) + (0.455 \times VM) \quad (1)$$

$$H\ (\%) = (0.052 \times FC) + (0.062 \times VM) \quad (2)$$

$$O\ (\%) = (0.304 \times FC) + (0.476 \times VM) \quad (3)$$

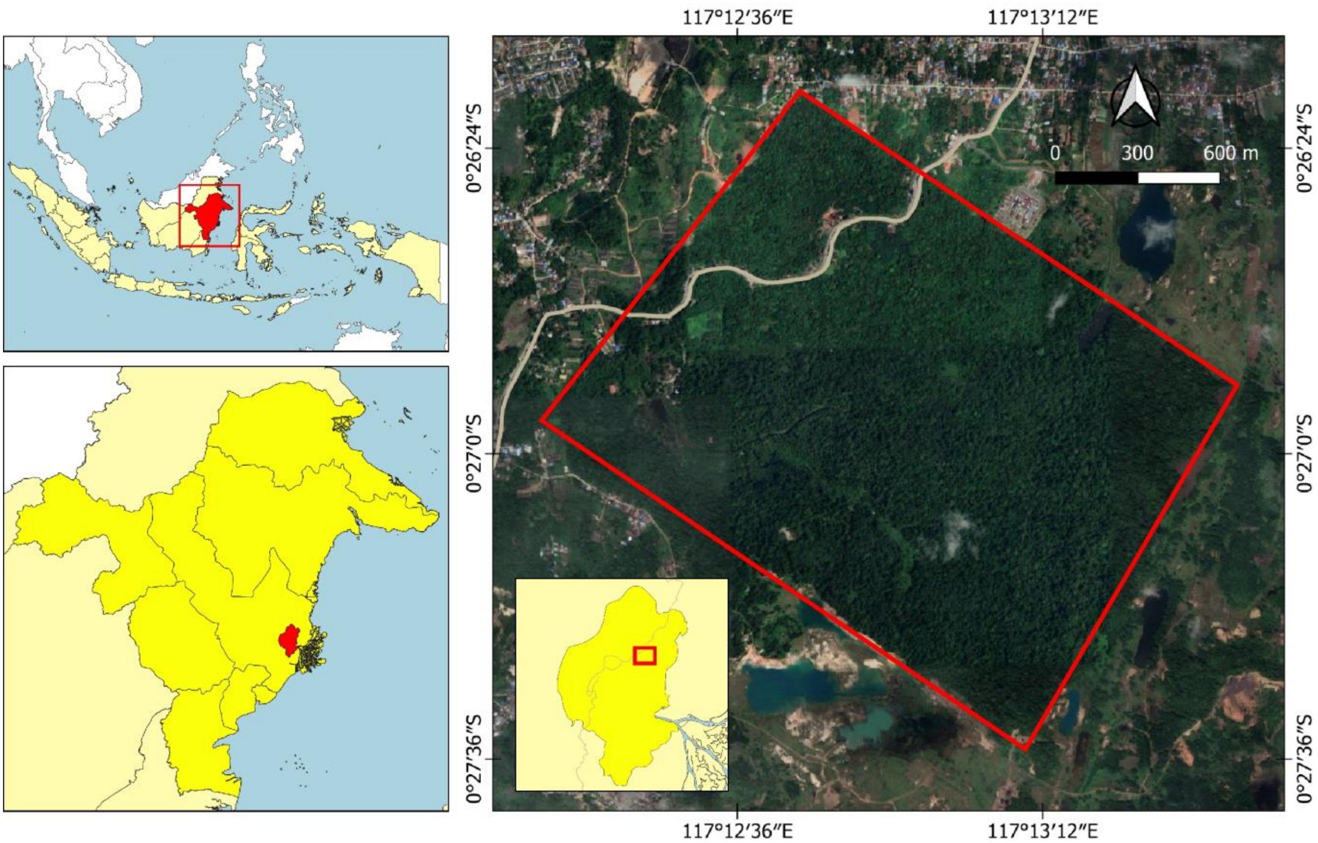

Figure 1. Research location conducted at Mulawarman University educational forest, Samarinda City, East Kalimantan Province, Indonesia (0°25’10” LS - 0°25’10” LS and 117°14’00” BT-117°14’14” BT).

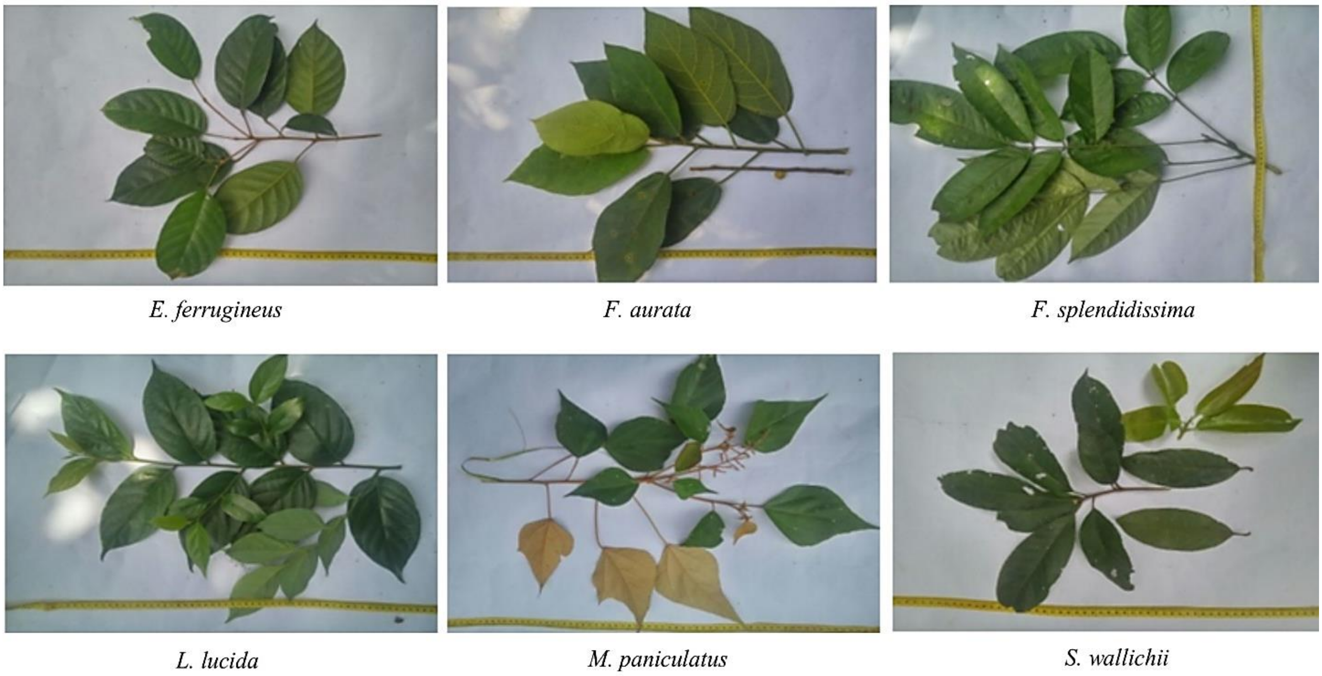

Figure 2. Fresh leaf shape varieties of some fast-growing native tree species were collected from the secondary forest of Mulawarman University educational forest, Samarinda City, East Kalimantan Province, Indonesia

Measurement of wood density (kg/m^3) was conducted by drying the wood samples at 105ºC following Edwards et al. (2014). The wood calorific value (MJ/kg) was accomplished in a bomb calorimeter according to the standard from EN-ISO 15400:2011, followed by the calculation of energy-electricity potency according to Francescato et al. (2008). Those measurements were classified into greenwood and wood chips. Furthermore, the fuel value index (FVI) was calculated using the equation as follows (Jain and Singh 1999):

FVI = (Calorific value x density) / (ash x moisture) (4)

RESULTS AND DISCUSSION

Plant biomass species

Generally, tropical forest areas provide better environmental conditions for plants to produce sustainable biomass with high yields. This condition will lead to its potential wide-range application in biomass-based conversion technology, such as electricity generation. However, a previous study demonstrated that forest biomass species with high energy content were commonly produced from low-growing species (Amirta et al. 2016). In large-scale electricity production, utilization of the low-growing species in energy feedstocks requires a slow harvest cycle period with a high-cost operation. Therefore, this study assessed woody materials obtained from selected fast-growing species, including *E. ferrugineus*, *F. aurata*, *F. splendidissima*, *L. lucida*, *M. paniculatus*, and *S. wallichii* for the purpose of energy-electricity feedstock. Those species are abundant and native to the secondary forest of East Kalimantan, in which the local people traditionally used their wood as firewood for cooking activities. Nevertheless, literature describing those plant species for further industrial application is still rare. The measurement of bark and wood proportion of each species was summarized in Table 1. It was noticeable that three species, including *E. ferrugineus, F. aurata,* and *F. splendidissima,* had the lowest bark-wood ratio (0.7). The highest bark proportion was obtained from *S. wallichiii*, followed by *M. paniculatus* and *L. lucida,* with the value of 12.95%, 11.22%, and 7.80%, respectively. It has been reported earlier that the stem bark of *E. ferrugineus* was the potential for treating malaria-like symptoms (Ismail et al. 2015). On the other hand, *S. wallichii* bark could be utilized as an antimicrobial agent (Dewanjee et al. 2008). Hence, these interesting properties could potentially enhance their application for both energy feedstocks and natural medicine products. Since the stem bark produces a high quantity of ash (Pérez et al. 2008), its removal from wood when used for energy production through thermochemical conversion is necessary.

Wood physicochemical properties

Moisture content, density, and chip capacity of woody materials examined from some selected native tree species were summarized in Table 2. It has been previously reported that the percentage of wood moisture content depends on the plant species, season, and storage condition (Mancini and Rinnan 2021). In green conditions, the highest wood moisture content was obtained from *S. wallichii* (59.25%), while the lowest moisture content could be found in *F. splendidissima* (40.37%). The conversion of the wood into chip form evidently reduced their moisture content. As shown in Table 2, all wood chips revealed a lower moisture percentage than green wood conditions. It was found that the average moisture content of wood chips was 9.58%. It seems that wood chip form could easily evaporate the amount of water. Surprisingly, this situation could also be benefited considerably increase the achieved calorific value due to the water loss phenomenon (Figure 3A). According to the measurement of wood density, it was found that the highest wood density was obtained from *F. splendidissima* (760 kg/m^3). The second and third largest were found in *E. ferrugineus* (575 kg/m^3) and *S. wallichii* (536 kg/m^3) wood, respectively. The average wood density value from all species used in this study was 507 kg/m^3. Meanwhile, their form changed into wood chips that needed a high storage capacity. It was found that the average value of wood chips of all species was 201 kg per m^3 of storage area. The high wood density contributed to increasing the efficiency of wood chip storage. As observed from *F. splendidissima,* its wood chip (300 kg/m^3) was the most efficient storage capacity among all woody materials used. Especially for a large-scale operation, the high density of wood chips potentially contributes to low energy production costs (Bahadori et al. 2014). In contrast, low wood density affects the fast burning of the reactor, high transport costs, and high storage capacity (de Oliveira et al. 2013).

Table 1. Wood and bark ratio of some fast-growing tree species native to the secondary forest of East Kalimantan, Indonesia

Plant species		Bark proportion (%)	Wood proportion (%)	Bark-wood ratio
Latin name	Local name			
E. ferrugineus	Belau	6.37 ± 0.59	93.63 ± 0.59	0.07 ± 0.01
F. aurata	Kayu ara	6.65 ± 0.25	93.35 ± 0.25	0.07 ± 0.00
F. splendidissima	Makumpit	6.70 ± 0.93	93.30 ± 0.93	0.07 ± 0.01
L. lucida	Madang	7.80 ± 0.55	92.20 ± 0.55	0.08 ± 0.01
M. paniculatus	Balik angin	11.22 ± 0.45	88.78 ± 0.45	0.13 ± 0.01
S. wallichii	Puspa	12.95 ± 0.68	87.06 ± 0.68	0.15 ± 0.01
Average		8.62 ± 2.79	91.39 ± 2.79	0.10 ± 0.10

Table 2. Moisture content, wood density, and chip capacity of some fast-growing tree species native to the secondary forest of East Kalimantan, Indonesia

Plant species		Moisture content (%)		Wood density	Chip capacity
Latin name	Local name	Greenwood	wood Chip	(kg/m³)	(kg/m³)
E. ferrugineus	Belau	49.77 ± 1.59	9.34 ± 0.03	575 ± 25.78	227± 10.18
F. aurata	Kayu ara	56.90 ± 0.63	9.62 ± 0.03	487 ± 23.19	192 ± 9.15
F. splendidissima	Makumpit	40.37 ± 0.19	9.81 ± 0.01	760 ± 22.69	300 ± 8.94
L. lucida	Madang	50.64 ± 1.05	9.64 ± 0.05	354 ± 14.86	140 ± 5.86
M. paniculatus	Balik angin	52.85 ± 0.28	9.52 ± 0.03	331 ± 11.21	131 ± 4.42
S. wallichii	Puspa	59.25 ± 1.83	9.53 ± 0.01	536 ± 18.99	211 ± 7.49
Average		51.63 ± 6.61	9.58 ± 0.15	507 ± 157.7	200 ± 62.6

Table 3. Proximate and ultimate analysis of some fast-growing tree species native to the secondary forest of East Kalimantan, Indonesia

Plant species	Ash (%)	Fixed carbon (%)	Volatile matter (%)	Carbon (%)	Hydrogen (%)	Oxygen (%)	H/C ratio
E. ferrugineus	2.29 ± 0.03	14.23 ± 0.18	74.14 ± 0.14	42.80 ± 0.18	5.34 ± 0.01	39.62 ± 0.12	0.12 ± 0.00
F. aurata	2.30 ± 0.02	13.53 ± 0.16	75.55 ± 0.17	42.54 ± 0.17	5.33 ± 0.01	39.60 ± 0.13	0.13 ± 0.00
F. splendidissima	1.62 ± 0.04	13.85 ± 0.13	74.72 ± 0.13	42.82 ± 0.14	5.35 ± 0.02	37.78 ± 0.10	0.12 ± 0.00
L. lucida	1.71 ± 0.02	14.82 ± 0.21	73.83 ± 0.21	43.03 ± 0.04	5.35 ± 0.01	39.62 ± 0.04	0.12 ± 0.00
M. paniculatus	2.69 ± 0.01	13.36 ± 0.10	74.43 ± 0.16	42.38 ± 0.13	5.31 ± 0.01	39.49 ± 0.10	0.13 ± 0.00
S. wallichii	1.64 ± 0.05	12.96 ± 0.16	75.87 ± 0.09	42.78 ± 0.14	5.38 ± 0.01	40.05 ± 0.09	0.13 ± 0.00
Average	2.04 ± 0.44	13.79 ± 0.66	74.76 ± 0.80	42.72 ± 0.44	5.34 ± 0.66	39.70 ± 0.80	0.13 ± 0.00

Various laboratory tests were carried out for proximate and ultimate analysis. The proximate analysis includes ash, fixed carbon, and volatile matter (Table 3). These parameters strongly affected the performance of combustion, pyrolysis, and gasification of wood biomass in the thermochemical conversion process (Tursunov and Abduganiev 2020). Ash content of all woody materials showed less than 5%, which demonstrated their high potency utilized for raw materials of energy production. The low value of ash residue (<5%) resulting from the combustion process has a positive impact on increasing the efficiency stage and avoiding damage to the electricity reactor (Shao et al. 2011). Nimmanterdwong et al. (2021) stated that the ash in biomass is directly related to the mineral and inorganic elements absorbed by plants from the ground via the root cells, while its percentage differently depends on the soil properties, rocks, chemical treatment, and available metal contents. The volatile matters of all woody materials in this study were in the range of 73.83 - 75.87%, whereas the fixed carbons were in the range of 12.96 - 14.82%. It has been reported that the heat decomposition of cellulose and hemicellulose in biomass is the source of volatile matter. In contrast, lignin is a char source due to its richness in carbon atoms (Vega et al. 2019). The ultimate compositions, including C (carbon), H (hydrogen), and O (oxygen), were presented in Table 3. This investigation is essential to determine the theoretical air-fuel ratio in the thermochemical system and predict the released pollution (Telmo et al. 2010). The average value of C, H, and O was 42.72%, 5.35%, and 39.70%, respectively. It was clearly observed that all woody materials contained C higher than O, indicating its high suitability used as the energy feedstock since high C content will increase the obtained calorific value. Moreover, the C content, with a value of more than 40% in this study, was in line with that of the C content of various tropical woods (Amirta et al. 2016; Amirta et al. 2019; Yuliansyah et al. 2019; Mukhdlor et al. 2021). Ratio of H/C was also assessed since a higher value could contribute to improving energy efficiency and decreasing released emissions during combustion (Gopalakrishnan et al. 2019). The average H/C ratio of the six-plant studied was 0.13. This value was comparable with sawdust previously reported by García et al. (2012). More importantly, these findings demonstrated that all fast-growing species selected in this study possessed better H/C ratio than those of other tropical fast-growing woody species, such as *Bridelia tomentosa*, *Fagraea racemosa*, *Piper aduncum*, *Trema orientalis*, and *Vernonia arborea* (Amirta et al. 2016).

Wood quality for energy feedstock

The investigation of the fuelwood quality of native species is presented in Figure 3. The important parameters were calorific value, wood chip conversion value, energy-electricity potency, and fuel value index. According to Figure 3A, the conversion of green wood (original solid form) into wood chip form significantly enhanced the average calorific value up to 0.5-fold. It was calculated that the average calorific value of all examined woods in the green form (7.92 MJ/kg) increased to 17.01 MJ/kg at the wood chip condition. We found that those results were in line with decreasing the amount of moisture content on wood samples when converted into wood chips (51.63% to 9.58%) (Table 2). It has also been reported by Deboni et al. (2020) that lower moisture content is considered one of the factors that significantly influence the increased calorific value of woody biomass as a reliable energy source. The high proportion of moisture content in fuelwood could result in delayed ignition and devolatilization (Lu et al. 2008). Although this work promised high energy content, the wood chip form consequently required a larger storage area (m^3) per ton of wood chip biomass than the greenwood form, as shown in Figure 3B.

In order to compare the suitability of woody materials from selected native species, further measurement of energy potency in MWh per ton biomass was performed (Figure 3C). The results showed that *F. splendidissima* exhibited the highest energy potency in both greenwood (2.21 MWh/ton) and wood chip (3.61 MWh/ton) forms. Although *S. wallichii* and *F. aurata* possessed high calorific values (Figure 3A), *F. splendidissima* had higher energy-electricity potency than those species due to its high wood density (760 kg/m^3). Interestingly, even though *F. splendidissima* is considered fast-growing species, this species was classified as high wood density (< 600 kg/m^3), whereas *S. wallichii* and *F. aurata* were characterized as medium wood density (400 - 600 kg/m^3). Having a similar pattern with calorific value results, the energy potency of all woody materials to generate electricity demonstrated significantly enhanced value after converting into wood chips due to the moisture removal. Our previous study shows fast-growing species in the lowland community forest, such as *Gmelina arborea*, *Anthocephalus cadamba*, *Acacia mangium*, and *Paraserianthes falcataria*, had relatively low energy potency (1.37 - 1.70 MWh/ton) (Amirta et al. 2016). Another study also reported that fast-growing and shrub species found in the tropical swamp-peat forest of Kutai Kartanegara in East Kalimantan generated low energy potency: *Kleinhovia hospita* (1.76 MWh/ton), *Cananga odorata* (1.36 MWh/ton), and *Octomeles sumatrana* (1.17 MWh/ton) (Amirta et al. 2019). However, our findings in this study indicated that fast-growing species native to the secondary forest in East Kalimantan, especially *F. splendidissima*, could produce woody materials with superior energy capacity for electricity production.

The bioenergy potential of each fast-growing native species was represented by Fuel Value Index (FVI) (Figure 3D). The FVI is an essential assessment for screening desirable biomass species for solid fuel (Samal et al. 2021). This measurement was also used by Niemczyk et al. (2018) to rank the quality of 10 poplar cultivars in northern Poland. The FVI was calculated using combinations of some influencing factors, including ash content, moisture content, calorific value, and wood density. This study found that wood chips containing low moisture content increased the FVI result from each wood tested. The average FVI of the wood chip, which had a value of 5267, was significantly higher than that of the greenwood condition, with an average value of 698. The greatest FVI was obtained from *F. splendidissima* (8970), followed by *S. wallichii* and *F. ferrugineus* with the value of 7502 and 4958, respectively. A high FVI value of wood biomass was observed because of low ash content, low moisture content, and high density (Pérez et al. 2014). We concluded that the wood chip revealed lower moisture content compared to the original form (green condition), indicating its high suitability to produce sustainable green energy.

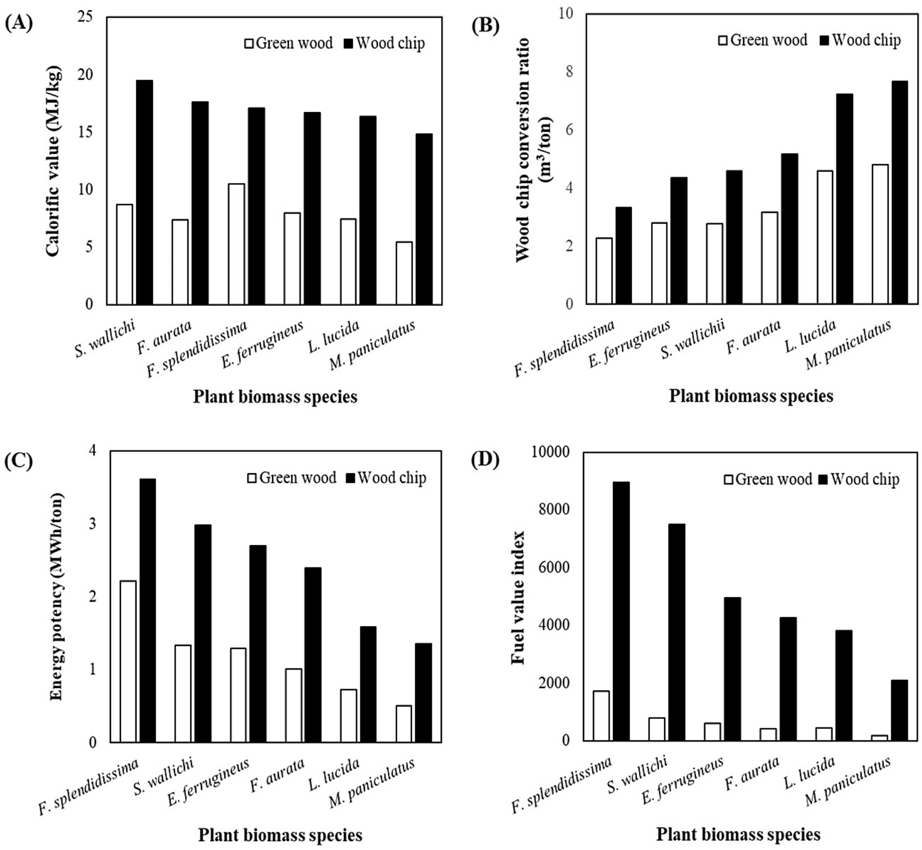

Figure 3. Analysis of some fast-growing tree species native to the secondary forest of East Kalimantan, Indonesia, for electricity feedstock: Wood calorific value (A), wood chip conversion ratio (B), energy potency (C), and fuel value index (D)

Finally, all woody materials obtained from fast-growing native species in the secondary forest of East Kalimantan were suitable for electricity feedstock due to the low ash content and a high proportion of carbon. When each wood biomass was converted into wood chip form, their efficiency in energy feedstocks (calorific value, storage capacity, energy-electricity potency, and FVI) was gradually increased since this form was able to remove moisture effectively. In contrast, the greenwood showed inefficient use since it might take longer to dry; thus, the cost of energy production will also increase. Among all biomass tested, the wood chip of *F. splendidissima* exhibited the most appropriate properties for electricity feedstock due to its high energy potency (3.61 MWh/ton) with desired FVI value (8970). Furthermore, the high adaptability in the local ecosystem combined with its high wood density and fast-growing ability will be the promising characteristics that allow *F. splendidissima* to be one of the ideal crops for energy feedstocks in the future. In general, this study successfully demonstrated the physicochemical properties of selected fast-growing native species in the tropical secondary forest in East Kalimantan, Indonesia, to generate electricity in rural communities, especially to develop the economic sector in this province.

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