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# 1 Mapping analysis of biomass residue valorization as the future green energy 2 generation in Indonesia

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10

## 11 ABSTRACT

12

13 Biomass residue is one of the focus areas for green energy in Indonesia, elaborated in  
14 Government Regulation no 79 the year 2014 on national energy development. The  
15 assessment of residual resources is an important way to show the availability  
16 distribution to realize the target of biofuel is more than 5% of the energy supply in  
17 2025. Thus, this paper will present a method to assess the energy production from  
18 biomass residue as a primary consideration in its development. Statistical data and  
19 field observations have been used to estimate the total availability of residue.  
20 Furthermore, to calculate the energy potential of biomass residue, the minimum and  
21 maximum value parameters, such as residue to product ratio, moisture content, and  
22 heating value, were obtained from works of literature. The power potential was also  
23 analyzed through three scenarios of the conversion factor efficiency, i.e., low,  
24 medium, and high, to provide comprehensive results.

25 The proposed methods allow the annual Indonesian biomass residue production  
26 from agriculture and forest residue to be nearly 155,271 and 2,554 tonnes,  
27 respectively. It can be generated an energy potential around 1261 PJ, covering 22.12%  
28 of national energy consumption. Given the high potential for sustainability in  
29 biomass residue supply and utilization, strategic factor in the areas of the government  
30 regulation and policy, greenhouse gasses emission, land-use change, and conversion  
31 technology were identified to support residue valorization in the context of planning,  
32 organizing and operating. The challenges and barriers that can be minimized by  
33 integrated collaboration and synergy among policymakers, entrepreneurs,

1 academics, and community to assist the sustainability of green energy production in  
2 the future, and evaluation of environmental, economic, and social analysis as a  
3 framework to improve the quality and quantity of the production processes.

4  
5 **Keywords:** *Biomass energy potential, agricultural residue, forest residue, timber processing*  
6 *residue*

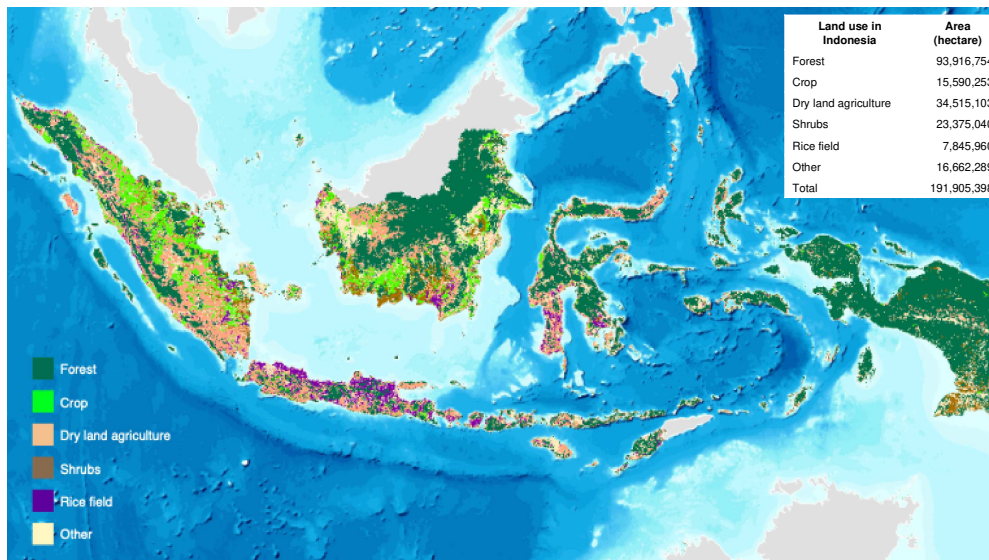
## 8 **1. Introduction**

9 Fossil fuel has a vital role in human-kind activities, which influence growth, development,  
10 and progress in all nations' economic, social and security sectors. Annually, the significant  
11 global energy demand continues to happen, fossil fuel consumption has increased by more  
12 than 50%, and it is expected to rise by another 18% over the next two decades (Yıldız, 2018).  
13 It can be potentially catastrophic in political, socio-economic, and environmental  
14 ramifications due to the overuse and depletion of energy reserve (Oyedepo, 2012). However,  
15 since implementing sustainable development goals, biomass energy sources are one of the  
16 solutions to reduce the problems. For example, natural gas can be partially substituted by  
17 biogas produced from food waste as the most voluminous solid waste via anaerobic  
18 fermentation (Maroušek et al., 2020). The charred bio-waste as a solid fuel can replace coal to  
19 support long-term energy supply by considering the economic and ecological aspects  
20 (Mardoyan and Braun, 2015). In the sustainability concept, waste cooking oil or vegetable oil  
21 can be processed as biodiesel to substitute diesel oil in specific applications (i.e. public  
22 transport and hybrid or marine propulsion) (Maroušek et al., 2020). Similarly, forest residue,  
23 such as palm oil fronds and leaves and rubber-wood sawdust, can replace 5% to 10% of  
24 gasoline applications in the transportation sector through bioethanol conversion (Hossain et  
25 al., 2021).

26 On the other hand, immediate application of biomass as clean energy due to the increase  
27 in crude oil price has forced the upgrading of biofuel production capacity (Oláh et al., 2017),  
28 which can be immense potential he environmental issues (e.g., land-use competition, land-  
29 use change, deforestation, and water supply pressure). Moreover, the land availability to  
30 cultivate the bioenergy crop has been slight. As a result, to minimize these problems, marginal  
31 and degraded land optimization is one of the sustainability solution to reduce the conflict  
32 between food, industry, and fuel production according to the community background (Edrisi  
33 and Abhilash, 2016). Therefore, these problems can also be solved by using biomass residues  
34 as a sustainable raw material for bioenergy.

1 Biomass residue utilisation has an enormous potential; several parameters must be  
2 considered, such as conversion processes and biomass characteristics based on the  
3 geographical, economic and social factors (Wang et al., 2017). In geographic view, climate and  
4 spatial model affect biomass's availability and distribution (Chinnici et al., 2015).  
5 Consequently, the impact of different geographic areas will determine the biomass residue  
6 properties, such as residue-to-product ratio, moisture content, and heating value. However,  
7 in the long term, biomass application can be a part of the solution to environmental problems.  
8 Several researchers have described the advantages of residue utilization in reducing  
9 greenhouse gas emissions (GHG). In Alberta, Canada, the utilization of agriculture and forest  
10 residue for energy production could be predicted to reduce 11–15% of GHG emissions by  
11 substituting 14–17% of total energy demand in 2030 (Weldemichael and Assefa, 2016). In Uttar  
12 Pradesh, India, biomass can reduce more than 50% to 80% of GHG emissions compared to  
13 fossil fuels (coal and natural gas) as a power source (Hiloidhari et al., 2019). If China can  
14 replace around 27% of fossil fuels with bioenergy, it will reduce GHG emissions by 49% by  
15 2050 (Kang et al., 2020).

16 Indonesia is an agrarian country whose land covers nearly 200 million ha, approximately  
17 48.96% of forest area and 31.77% of agriculture area in 2018 (Fig 1). Almost all of the forest  
18 land is used for dryland forest (74.57 million ha), while agriculture land is cultivated for rice  
19 and cereals (7.88 million ha) (“Statistics Indonesia,” 2020). Given the fact that there is vast  
20 biomass potential as a sustainable energy feedstock, there is an abundant residue that can be  
21 converted to heat and electrical energy forms. However, most of the residue was burned in  
22 the field area, and a small amount was utilized as feed, burned as fuel for cooking in  
23 households and small industries, as fertilizer, or left on the farm for soil conservation.  
24 Farmers' most well-known method of lowering costs and time is open burning in the field  
25 area, but the activity harms the health of nearby communities, soil structure, biodiversity, and  
26 air pollution. There is no comprehensive data on the quantity and distribution of Indonesian  
27 biomass residue on a local, regional, and national scale, nor any record of the total used and  
28 disposed of at the final landfill. However, when the phenomena are associated with the  
29 national energy planning goals according to Presidential Regulation No. 22 The years 2017  
30 which explains that in 2025 and 2050, biomass could generate electricity at about 5.5 GW and  
31 26 GW, respectively, the opportunity for biomass residue valorization is highly open for  
32 commercial purposes in all regions. Thus, the assessment of biomass residue as a basis to  
33 implement these programs considers the model of sustainable development.



**Fig. 1.** Indonesian spatial data of the land use in 2018

To evaluate the sustainability of biomass residue resources, the global scale, scope, and boundary must be determined as a basic calculation. Furthermore, the biomass potential types (e.g., theoretical, technical, economic, and implementation potential) as an important parameter in deciding the assessment approach using one of the following approaches: resource-focused, demand-driven, or integrated approaches (Batidzirai et al., 2012). Many researchers have analyzed the residual resources for bioenergy production in some regions with various approaches and methods. In this article, the complete literature review of the methodology of biomass residue assessment is presented in the Supplementary Document.

The study aims to assess Indonesia's sustainable biomass residue potential for bioenergy purposes. The specific objectives have been set to achieve the overall goals: to identify and calculate the total residue and energy production in national scale by using the statistical and government report; to estimate the power energy generation, the energy efficiency scenarios have been used according to the literature review, and to support the biomass energy development as a national energy substitution, and the strategic factor will describe to determine the future perspective of residue utilization.

The results will provide comprehensive information on biomass residue potential across Indonesia. Favorable results could be helpful to increase awareness and promoting of residue utilization as sustainable energy sources in the future. Producing green energy from agriculture and forest residue could have a positive impact on the community and environment, such as strengthening the energy security, improving the social-economic, reducing environmental problems, and decreasing dependence on fossil fuel.

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## 2. The strategic factor for biomass residue development in Indonesia

The current debate about the future of bioenergy is focused on how to best generate green energy by utilizing biomass residue based on technological advancement, environmental benefits, and socioeconomic potential. It should consider the embeddedness of the last issue in a macro system in which the influence factors of biomass residue utilization interact and can hardly be separated. In this section, the supporting view points of biomass residue utilization will be explained in detail, i.e., government regulation and policy, greenhouse gas emissions, land-use change, and technology development.

### 2.1. Government regulation and policy

The sustainability of Indonesia's energy supply is a significant challenge due to the gradually increases demand annually. In 2020, the total primary energy supply, i.e., coal, oil, natural gas, biomass and other renewable energy, reached 3388.83 PJ, 2891.96 PJ, 1536.46 PJ, 326.48 PJ and 186.17 PJ, respectively. Whereas the total consumption is nearly 5497 PJ, composed of 43% of transportation, 34% of the industry, 16% of households, 5% of commercial, and 2% others. To mitigate these problems, the fossil fuel reserve continually depletion and global commitment to reduce greenhouse gas emissions improve Indonesian government is committed to enhancing national energy security, one of which is through biomass energy production. It has been proven by the policies and regulations that are related to biomass development (See Supplementary Materials).

Traditional biomass utilization is associated with side effects on the environment, such as indoor air pollution and deforestation. The replacement of modern biomass energy combined with more efficient technology conversion needs the guarantee of quality. It is clear that Indonesia has a huge potential for competitiveness to improve its biomass energy output. This should be supported by the standardization of biomass products like in developed countries. For example, the European Union has guidance of EN 14961-2 to guarantee the quality of wood pellets sold in the market (Duca et al., 2014). The South Korean government stated that the biomass pellets produced and exported must have comparable properties to the Wood Pellet Quality Standard from the Korea Forest Research Institute (Oh, Jae-Heun et al., 2014). While France does not have official wood pellet standards, it has established quality control (ITBE) based on the combustion installation type, such as stove, boiler, and incinerator (Garcia-Maraver et al., 2011). Denmark, the Netherlands, and the United Kingdom require a supplement to the biomass power plant's periodic report on the land sustainability assessment result and air pollution produced by its operation (Thrän et al., 2019). To realize the national

1 green bioenergy goals, the Indonesian government's participation is important through  
2 issuing the rules and guidance on the criteria and requirements for biomass process and  
3 output that reflect environmental sustainability and market trust.

4 The government programs that have been launched to support biomass energy  
5 development according to the Indonesian President Regulation No. 72 the year 2017 on  
6 national energy plans are: 1) guarantee the biomass supply and feedstock; 2) improve the  
7 quantity and quality of biomass potential survey; 3) construct the biomass power plant to  
8 equalize access to electricity; 4) promote non-edible food as biomass sources; and 5) research  
9 and development of biomass technology. Currently, the big challenge is the low price of coal,  
10 but the Indonesian government has issued a regulation on the coal price. In November 2019,  
11 the Minister of Energy and Mineral Resources' decision No 224K/30/MEM/2019 explained  
12 that the estimated fee of coal per ton was approximately USD 66.27. While in December 2018,  
13 the cost per ton of coal was more expensive 40% that is accordance with the Minister of Energy  
14 and Mineral Resources' decision No 2025K/30/MEM/2018. The coal operational fee per kWh  
15 of electricity generated was set at 0.05 US dollars. It contrasted condition with the micro-hydro  
16 and geothermal value of 0.06 US dollars and 0.08 US dollars, respectively. It means that the  
17 assumption is that conventional power plants the economic operating costs.

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34 output that reflect environmental sustainability and market trust.

## 1        2.2. *Greenhouse gasses emissions*

2        Greenhouse gas emissions are a continuing contentious issue in any energy sector, except  
3 biomass energy. Biomass energy can have positive value in reducing GHGs, particularly  
4 when applied in sustainable production and management contexts. For example, when  
5 biomass is applied efficiently to generate electricity and heat by modern conversion  
6 technology, but the traditional application in households has a role in creating indoor air  
7 pollution when the utilization does not observe environmental criteria. It should be noted that  
8 biomass application is related to technology conversion, therefore it needs a detailed  
9 environmental assessment through Life Cycle Assessment (LCA) to discover the precise  
10 percentage contribution to GHG's.

11        When the biomass residue is not utilized optimally and the amount is abundant, this is  
12 the major contributor to GHGs in post-harvest activity. Most farmers in developing countries  
13 prefer burning the biomass residue in the field compared to managing it as a bioenergy  
14 source. Overall, they have the perception that open burning can minimize the cost and time  
15 of management for the next planting. In fact, this activity can damage the soil structure due  
16 to diminished soil nutrients and be a reason for erosion in the long term (Chen et al., 2017). In  
17 Indonesia, during the dry season from August to September, the open burning of rice residue  
18 almost happened in a part of Java Island (i.e., East Java, Central Java, and West Java provinces)  
19 and South Sumatera province as a leading agricultural areas (Permadi and Kim Oanh, 2013).  
20 In 2015, it could be estimated that the production of GHGs emmissions reached 20,874.55 Gg  
21 per year CO<sub>2</sub>; 3,088.27 Gg per year CO, 164.63 Gg per year CH<sub>4</sub>, 53.22 Gg/year NO<sub>x</sub>, 34.33 Gg  
22 per year SO<sub>2</sub> and 51.33 Gg per year OC, respectively (Andini et al., 2018). To mitigate these  
23 phenomena, the rising public awareness is needed through the education and training about  
24 GHG's impact on environment and more important how to increase the benefits of biomass  
25 residue as a sustainable energy source by taking note of the material and technological  
26 purposes. It is supported by the government role to promote the biomass energy on  
27 transportation and industrial sector, to reduce roughly 5% of CO<sub>2</sub> emissions annually

## 28        2.3. *Land-use change*

29        In recent years, the land-use change was a fundamental problem in globalization and  
30 industrialization. It has an impact on the gradual decrease in agriculture area and  
31 deforestation. In the bioenergy scenario context, reducing GHG emissions also provokes land  
32 use competition in the long term. Therefore, crop residue utilization as bioenergy could be a  
33 simple solution to synergi between food and energy security (Lambin and Meyfroidt, 2011).



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4 competition in the long term. Therefore, crop residue utilization as bioenergy could be a  
5 simple solution to synergy between food and energy security (Lambin and Meyfroidt, 2011).  
6 To support these solutions, since the last decade, the degraded land restoration program has  
7 promoted the production of bioenergy from non-edible oils, such as nyamplung  
8 (*Calophyllum inophyllum* L.) and *Jatropha curcas*. It was proven that nearly 50% of degraded  
9 land is a significant decrease of about 14.01 million ha in 2018 compared to 2011 (Statistik  
10 Indonesia). In general, the critical land use integration for green energy production has several  
11 benefits for the environment, i.e., it minimizes the impact of unlimited carbon storage,  
12 prevents soil erosion, and maintains biodiversity (Blanco-Canqui, 2016). Moreover, it has  
13 created new job prospects in rural areas to improve the socio-economic situation of the  
14 community (Dauber et al., 2012).

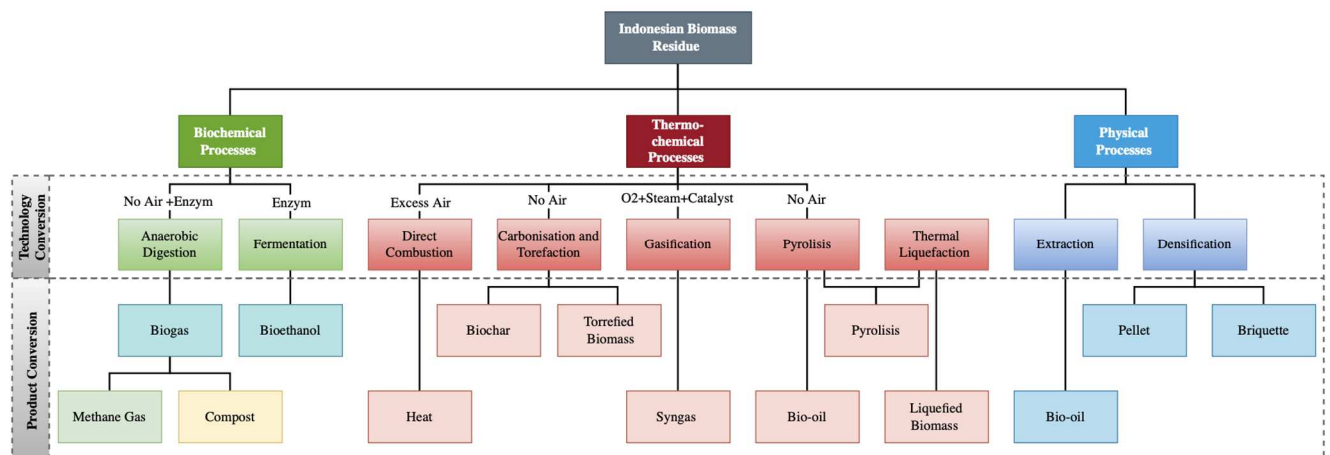
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21 biodiversity (Blanco-Canqui, 2016). Moreover, it has created new job prospects in rural areas  
22 to improve the socio-economic situation of the community (Dauber et al., 2012).

23 Few models were developed to review the effect of land-use change on biofuel production;  
24 for instance, the GHG emissions can determine land-use change decisions during the biomass  
25 energy production by Calculating Uncertainty in Biomass Emissions (CUBE) model  
26 (Curtright et al., 2012). A separate method was used to assess the land-use change by  
27 mitigating impacts on perennial plants due to mapping and quantifying the degree of  
28 accumulated soil organic carbon losses by wind and water erosion, nitrogen emissions to  
29 water, and recurring floods (Englund et al., 2020). The economic model is also applied to  
30 explain the correlation between land-use change, the economy, and biomass production for  
31 electricity (Fargione et al., 2010). The existence and application of bioenergy policies  
32 determine the demand proportion of land utilization in agricultural and marginal lands  
33 (Warner et al., 2013). The important point to note, however, is how the sustainable program  
34 minimizes land-use change while supporting the community's social-economic well-being.

1 The sufficient energy village (Desa Mandiri Energi) is one of the implementations to manifest  
 2 minimalizing land-use change. The first key is to strengthen collaboration among farmers,  
 3 government, industry, and academics by increasing farmer awareness and participation in  
 4 crop residue utilization, facilitating infrastructure provision and market share through  
 5 cooperation and institutional development, and sharing information through education and  
 6 training to improve sustainable cultivation programs. To optimize these, government  
 7 regulations and policies have been issued to protect land-use change, which impacts  
 8 environmental issues and biomass energy supply (see Supplementary Document).

9 *2.4. Biomass technology conversion*

10 Agricultural and forest residues have a huge potential as bioenergy, which can be  
 11 transformed into solid fuel (i.e., pellets and briquettes), liquid fuel (i.e., biodiesel and  
 12 bioethanol), and gas in the form of syngas. The biomass conversion technology is a major  
 13 factor in generating the quantity and quality, but it should be noted that crop type, cost of  
 14 handling, and emission level were also factors. For example, secondary industrial waste has  
 15 a high moisture content and is not suitable for being converted by thermochemical, but it is  
 16 suitable for being converted via biochemical. The utilization of each conversion method has  
 17 some benefits, which follow the purpose of the biofuel produced. There are three main  
 18 processes for transforming biomass into bioenergy that are thermochemical, biochemical, and  
 19 physical. The representation of biomass residue development in Indonesia can be described  
 20 in Fig. 2.



21  
 22 **Fig. 2.** Indonesian biomass residue processes

23 The thermochemical conversion uses high heat energy to resolve the bond of the organic  
 24 matter through devolatilised, depolymerise, and oxidised activities into biochar (solid),  
 25 synthesis gas and bio-oil (liquid) (Lee et al., 2019). This process involves direct combustion,  
 26 pyrolysis, gasification, torrefaction, carbonisation and thermal liquefaction (Dayton and

1 Foust, 2020). More over, It has high efficiency and quicker reaction time than biochemical  
2 activity, but it depends on the operational temperature and environmental conditions (Adams  
3 et al., 2018). Contrary to thermo-chemical process, the biochemical process needs biological  
4 activators such as enzymes, bacteria, yeast and biocatalyst, for degrading the biomass  
5 structure in conversion processes. There are two methods to transforming i.e., fermentation  
6 to produce bioethanol and anaerobic digestion to generate biogas (Dayton and Foust, 2020).  
7 Lastly, the physical process uses mechanical force to convert biomass to solid fuel through the  
8 densification process or bio-oil via extraction. The physical process uses mechanical force to  
9 convert biomass into solid fuel through densification and extraction. Moreover, the physical  
10 process is a pre-treatment to make material handling easier.

11 In Indonesia, the most widely applied biomass conversion technologies on small scales  
12 are direct combustion, carbonizing, and biogas. In the case of electricity production, the  
13 thermo-chemical conversion via the gasification process has operated in recent years as a  
14 power plant. At the end of 2018, the palm oil residue was utilized as a raw material at biomass  
15 power plant in Siantan, Kalimantan, generating annual electrical production roughly 0.27 PJ.  
16 In the third quarter of 2019, the bamboo residue could generate 5.1 TJ per year in Siberut  
17 Island. However, the biomass transformation will continue to be refined to achieve the  
18 national plan of biomass energy, which is to reach 5.5 GW in 2025 and 26 GW in 2026.

### 19 **3. Materials and methods**

20 The estimation of Indonesian biomass residue potential energy considers the amount of  
21 energy available from each residue resource. Firstly, calculate the total residue during the  
22 temporal cycle in all regions, which depends on crop properties and energy content.  
23 Furthermore, a scenario is adopted to define the detailed range of energy that predicts the  
24 electrical energy potential.

#### 25 *3.1. Study Area*

26 Indonesia is located between 6° northern latitude and 11° southern latitude and 95° - 141°  
27 east meridians, part of the Southeast Asia region, cover 1,904,569 km<sup>2</sup>. As shown in Fig. 1,  
28 agriculture and forest covered nearly 61 and 94 million hectares, respectively. In the  
29 agriculture sector, the main commodities are rice, corn and cassava in the food crop and  
30 palm oil in the plantation crop. In 2019, food crops production slightly decreased by 7.76% in  
31 rice, while corn and cassava gradually increased by 3.91% and 1.51%, respectively. Those  
32 quantities were recorded approximately 54,60 million tonnes of rice, 29.90 million tonnes of  
33 corn and 16.52 million tonnes of cassava. Moreover, Indonesia is the largest producer of palm  
34 oil, accounting for nearly 43% of the world's palm oil production (Widiyanto et al., 2019). In

1 the forest sector, total log production roughly increased 4.36% in 2019, reaching 57.93 million  
2 m<sup>3</sup>. At the same time, the processed timber production, such as chips and particles, plywood,  
3 swan timber, veneer, and fibreboard are around 29.73 million m<sup>3</sup>, 3.99 million m<sup>3</sup>, 2.59 million  
4 m<sup>3</sup>, 2.10 million m<sup>3</sup> and 0.5 million m<sup>3</sup>, respectively (Subdirektorat Statistik Kehutanan, 2020).

5 In the energy view 2019, Indonesia's primary energy supply consisted of 35% oil, 37.3%  
6 coal, 18.5% natural gas, 2.5% hydropower, 1.7% geothermal and 3% biofuel (MEMR, 2019). In  
7 the last decade, primary energy demand has increased by 3% per year, while energy  
8 consumption rose from 0.017 TJ per capita in 2016 to 0.021 TJ per capita in 2019 (BP, 2019).  
9 Indonesia also has a huge potential for renewable energy sources, (e.g. solar, wind, hydro,  
10 biomass, ocean and geothermal), has an estimated value of approximately 1.59 PJ (MEMR,  
11 2019). It has great potential to develop green energy programs to reduce GHG emissions.

### 12 3.2. *Data sources and collection*

13 This investigation focused on agriculture and forests residue that is are subject to possible  
14 exploitation as an energy source. Several agriculture products, such as food crops (i.e. rice,  
15 maize, cassava, groundnut, and soybeans) and plantation crops (i.e. sugarcane, coconut, palm  
16 oil, coffee, and cocoa) are principally commodities in all the Indonesian areas throughout year.  
17 The availability of forest products derived from the harvesting of natural forests (i.e. Acacia  
18 sp., Eucalyptus sp, Tectona grandis LF, Meliaceae, and Albizzia falcataria), industrial forest  
19 plantations (i.e. Shorea spp, Mixed forest, Intsia bijuga and Dipterocarpus borneensis), and  
20 wood processing mill residues considered from technical, ecological, and sustainability  
21 aspects due to the limitation of forest production.

22 To achieve the research goal, the annual crop production and cover harvested area have  
23 been drawn from statistical data collected over ten years by the Indonesia Central Bureau of  
24 Statistics (BPS). Specifically, the annual report and strategic documents from the Agriculture  
25 Ministry (i.e., the Outlook Food Crop Report and the Outlook Plantation Crop Report started  
26 in 2010 to 2020) to discover the geographic location of the products. The major information on  
27 wood and timber processing yield and distribution was obtained from the Forest Production  
28 Statistics Report started in 2010 to 2020 by the Environmental and Forestry.

29 In this study, the physical properties of biomass residue, such as moisture content (M),  
30 residue-to-product ratio (RPR), and lower heating value (LHV) of dry matter, were obtained  
31 from numerous studies in the last 20 years to maintain data accuracy and validity (See  
32 Appendix A and B).

33 The availability factor (A) used the literature review as a basis study to estimate the  
34 amount of residue for bioenergy purposes. A random sampling of the residues was performed

1 by interviewing 100 stakeholders (i.e., farmers, agriculture and wood suppliers, agricultural  
 2 extension, researchers in agriculture and forestry agencies, and academics) to recognize the  
 3 biomass residue availability in post-harvest. The sampling locations are in several provinces  
 4 on Java Island, such as East Java, Central Java, and West Java for the agriculture sector. And  
 5 in Kalimantan island, i.e., East Kalimantan, Central Kalimantan, and East Kalimantan for  
 6 forestry products. The main reasons for selecting these are the high biomass residue potential  
 7 due to above-average production and harvested area. To validate these data, the minimum  
 8 and maximum value are applied to calculate the numerical data of biomass residue properties  
 9 by a mathematical model (See Appendix).

### 10 3.3. Key parameter to assessment biomass residue

11 The energy potential of agriculture and forest residue is estimated in this section.

#### 12 3.3.1. Theoretical potential quantity of biomass residue

13 The Residue-to-Product Ratio (RPR) related to total residue was generated from a tonne  
 14 of harvested dry crop production. For example, the RPR of rice straw is 1.75, which means  
 15 that a tonne of total rice production on a dry basis could generate 1.75 tonnes of rice straw  
 16 according to the physical characteristics, cultivation method, and crop variety. RPR value as  
 17 the basis to estimate the Theoretical Biomass Residue Potential (TBR) quantity. To calculate  
 18 the TBR of agricultural residue, Eq. (1) is used, (Di Fraia et al., 2020).

$$19 \quad TBR_{AR} = \sum_{i=1}^n HA_{(i)} \times P_{(i)} \times RPR_{(i)} \times (1 - MC_{(i)}) \quad (1)$$

20 Where  $HA_{(i)}$  is the annual harvested area of crop in hectare per year,  $P_{(i)}$  is the annual  
 21 productivity of crop in tonne per hectare per year,  $RPR_{(i)}$  is the residue to product ratio, and  
 22  $MC_{(i)}$  is moisture content of crop residue in percentage term.

23 The theoretical quantity of forest biomass residue depends on the ~~density~~ of wood density  
 24 and the recoverability factor related to the generated timber residue. The wood's density was  
 25 obtained from the open-access database of tree density on the website  
 26 <http://db.worldagroforestry.org>. In contrast, the density of timber processing was obtained  
 27 from the Ministry of Environmental and Forestry data and field observation, which is similar  
 28 to determining the availability factors (see Section 3.2). To calculate the TBR of forest residue  
 29 can be expressed in Eq. (2), (Di Fraia et al., 2020).

$$30 \quad TBP_{FR} = \sum_{i=1}^n AP_{(i)} \times \rho_{(i)} \times R_{(i)} \times (1 - MC_{(i)}) \quad (2)$$

31 Where  $AP_{(i)}$  is the annual production of wood product in ton per year,  $\rho_{(i)}$  is the density  
 32  
 33  
 34

1 of wood in kg m<sup>-3</sup> and R<sub>(i)</sub> is the recoverability factor of timber. In this study, logging and  
 2 wood processing residue recoverability factors were 0.25 and 0.42, respectively (Mboumboue  
 3 and Njomo, 2018a). In Indonesia, the residual factors reach 30.5% and 16.4% of natural and  
 4 industrial forests in Kalimantan, Papua, and Sumatra. Those indicate that every 1m<sup>3</sup> of log  
 5 produced 0.351 m<sup>3</sup> and 0.153 m<sup>3</sup> residues from natural woods and industrial forest and timber  
 6 manufacture (i.e. plywood, sawdust wood and veneer) reach 0.6 m<sup>3</sup> (Simangunsong et al.,  
 7 2017).

### 8 3.3.2. Availability Potential of Biomass Residue

9 The Availability Biomass Potential (ABP) is calculated from the total residue production  
 10 for bioenergy purposes after deducting for other purposes (e.g. animal feed, fertilizer, etc).  
 11 More competitive uses of biomass residue mean less availability of biomass. The availability  
 12 value of each crop in each area dramatically varies according to the harvesting methods and  
 13 equipment. For example, when rice harvesting, the height of the cutting and threshing process  
 14 influences residue production. The straw and husk that are generated using manual  
 15 techniques and have an uncertain quantity compared to the agricultural machinery. The  
 16 availability factor is a basics for evaluating the availability of biomass residue, as given in Eq.  
 17 3, (Avcioglu et al., 2019).

$$18 \quad ABP_{(i)} = \sum_{i=1}^n TBP_{(i)} \times A_{(i)} \quad (3)$$

19 Where A<sub>(i)</sub> is the availability factor of biomass residue as a percentage.

### 22 3.3.3. Energy potential of biomass residue

23 The Energy Potential of Biomass (EPB) could be estimated by biomass's lower heating  
 24 value (LHV) on a dry basis, as presented in Eq. 4, (Avcioglu et al., 2019).

$$25 \quad EPB_{(i)} = \sum_{i=1}^n APB_{(i)} \times LHV_{(i)} \quad (4)$$

### 28 3.3.4. Power potential of biomass residue

29 Biomass residue can be converted to reen energy by precise technology selection. The  
 30 efficiency of energy process production depends on crop residue (moisture content) and its  
 31 route. There are two types of biomass energy conversion, i.e. thermochemical conversion and  
 32 bio-conversion, which have certain moisture content requirement. The thermochemical  
 33 conversion is more suitable to generate and store heat, mechanical power, and electricity  
 34 ompared to bio-conversion (Singh et al., 2007). For any types of biomass residue, the

1 thermochemical process efficiency ranged from 20 to 40% (Singh, 2015). The amount of power  
2 potential biomass (PPB) as presented in Eq. 5, (Román-Figueroa et al., 2017).

$$3 \quad \text{PPB}_{(i)} = \sum_{i=1}^n \frac{\text{EPB}_{(i)} \times \eta e_{(i)}}{3600 \times \text{OH}_{(i)}} \quad (5)$$

4  
5  
6 Where,  $\eta e$  is an efficiency conversion factor, in this study, the efficiency factors use three  
7 levels, i.e. low, medium and high efficiency were 20, 30, and 40%, respectively.  $\text{OH}_{(i)}$  is the  
8 time operation of technology conversion in an hour, in this case, 8000 hours per year.

#### 9 **4. Results and discussions**

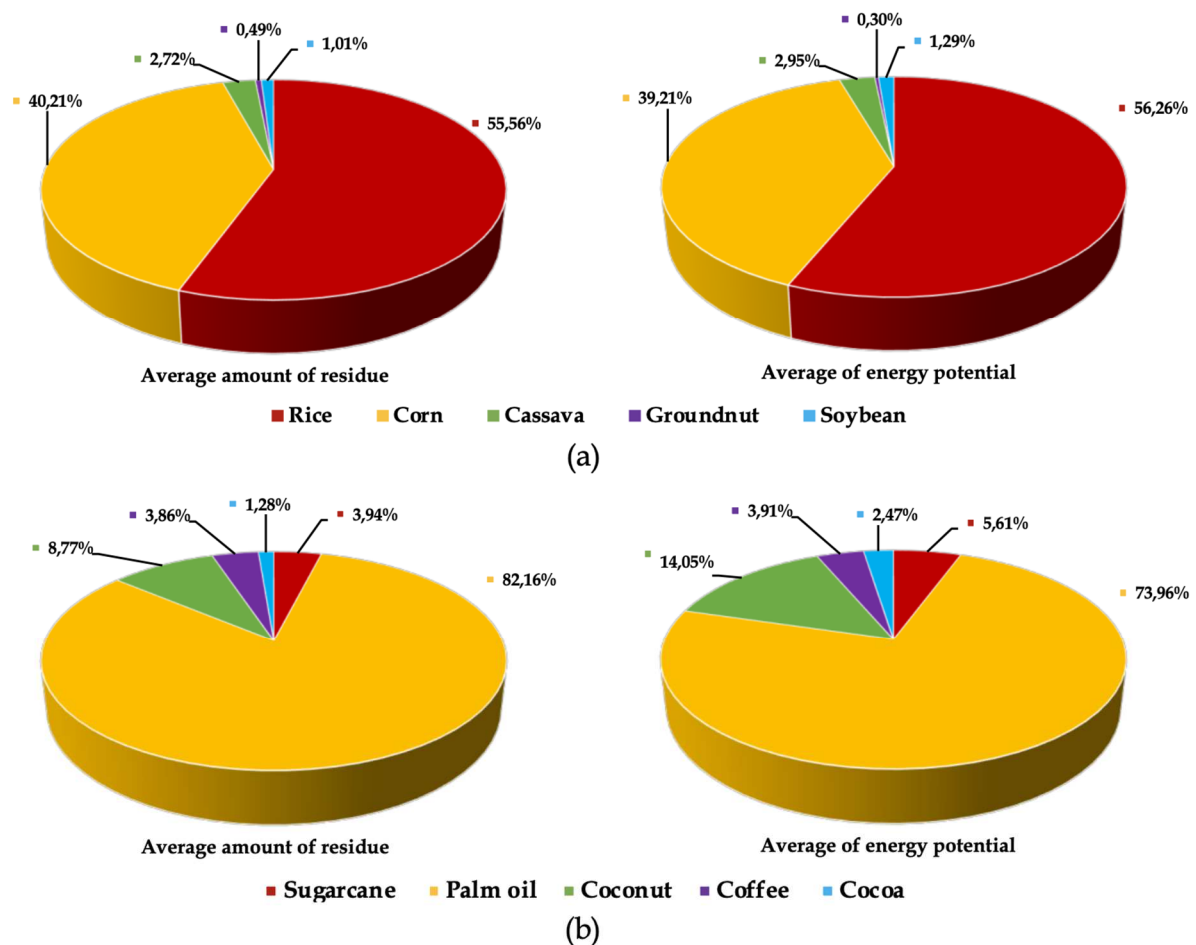
10 The theoretical availability, energy potential and power potential Indonesian biomass  
11 residue potential from agriculture and forest sectors were estimated by Eq. (1) - (5), based on  
12 Tables 1 and 2.

##### 13 *4.1. Agriculture residue energy and power potential*

14 In recent decades, the annual average agriculture production has reached 136.22 million  
15 tonnes, with the top ten commodities recorded. The analysis by Eq. (1) - (3) shows that rice,  
16 corn and palm oil ranked in the first three places of agriculture product, with 75.97; 54.98 and  
17 15.24 million tonne of dry biomass residue, respectively. Rice straw and husk, and maize cob  
18 and stalk as food crops have great opportunities to be converted into bio-energy through  
19 densification processes due to their their being found in most areas in Indonesia regions.  
20 Otherwise, palm oil as a plantation crop is only cultivated in a part of Sumatra, Borneo,  
21 Celebes and Papua island. However, palm oil residue (i.e. empty fruit brunch, shell and fibre)  
22 has been utilized as a raw material in biodiesel production due to the Indonesian  
23 government's mandate to mix 20% biodiesel (B20) starting in 2018. The result of this study  
24 estimated the energy potential of agricultural residue at more than 300 PJ.

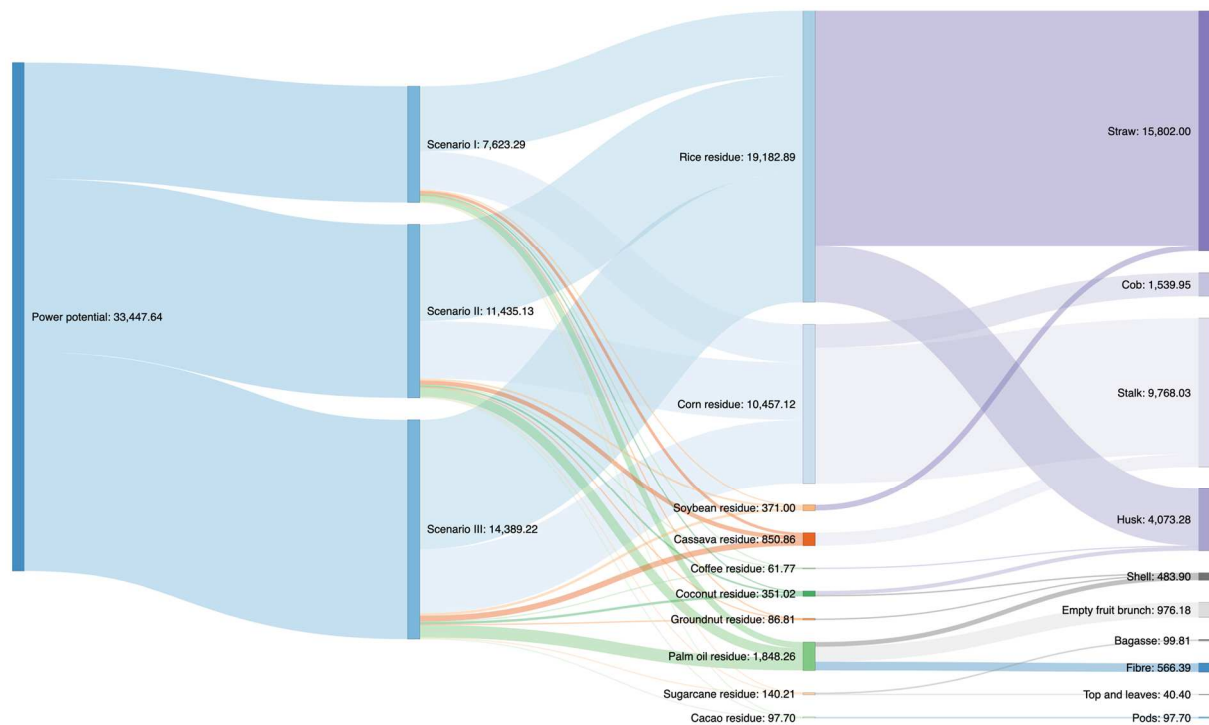
25 Fig. 3 present the total availability residue production and energy potential for (a) food  
26 and (b) plantation crop during 2011 - 2020. Rice straw and husk have half the total residue of  
27 food crops and can generate over 50% of their energy potential. While palm oil is a plantation  
28 crop produce 82% of residue, it can generate nearly 60% of its energy potential. It has to be  
29 underlined that the biomass characteristics were taken into the maximum and minimum  
30 limitation values. Furthermore, several properties, such as productivity and RPR have an  
31 essential role in determining the amount of residue, but the moisture content on a dry basis is  
32 the final factor to show the total residue production. Finally, the LHV is the main factor to  
33 calculate the energy potential of residue. The analysis results reflect that rice, corn and palm  
34 oil can be promote as food and energy security for future investment. In addition, the

1 cultivation geography, such as location altitude, weather, soil quality and water resources has  
 2 influence on the physical properties of the crop. The harvesting methods and agricultural  
 3 machinery also have a relationship with the residue yield. For example, in rice harvesting, the  
 4 utilization of a rice harvesting machine will produce a homogenous size of straw compared  
 5 to the manual method of using a sickle. When the crops produce the highest amount of  
 6 residue, it could be considered to plan and create the supply chain for biomass valorization.  
 7 The main supports for launching sustainable bioenergy generation are stakeholder  
 8 awareness, policy and regulation, and infrastructure.



9  
 10 **Fig. 3.** Residue production availability and energy potential of agricultural sectors in  
 11 Indonesia, where (a) food crop and (b) plantation crop





**Fig. 4.** Sankey diagram: annual average power potential of agricultural sectors in Indonesia

The agriculture residue as power generation were analyzed by three scenarios of efficiency conversion factor and time operation of 8000 hours per years (Fig. 4). When Eq. (5) has applicated to calculate the agriculture residue and efficiency factors 20, 30, and 40% would generate around 7623.29, 11435.13, and 14389.22 MW of power potential, respectively. Straw, stalk, and husk generate the most power in all scenarios when compared to other residues. When the efficiency factor is at its minimum value (20%), the power potential of straw, stalk and husk residue reaches 3429.11, 1981.59 and 833.75 MW, respectively. The gradual increase in conversion factor will significantly increase power generation. Hence, the efficiency factor is the most crucial point. In deciding the power plant design and technology with biomass raw materials.

#### 4.2. Forest residue energy and power potential

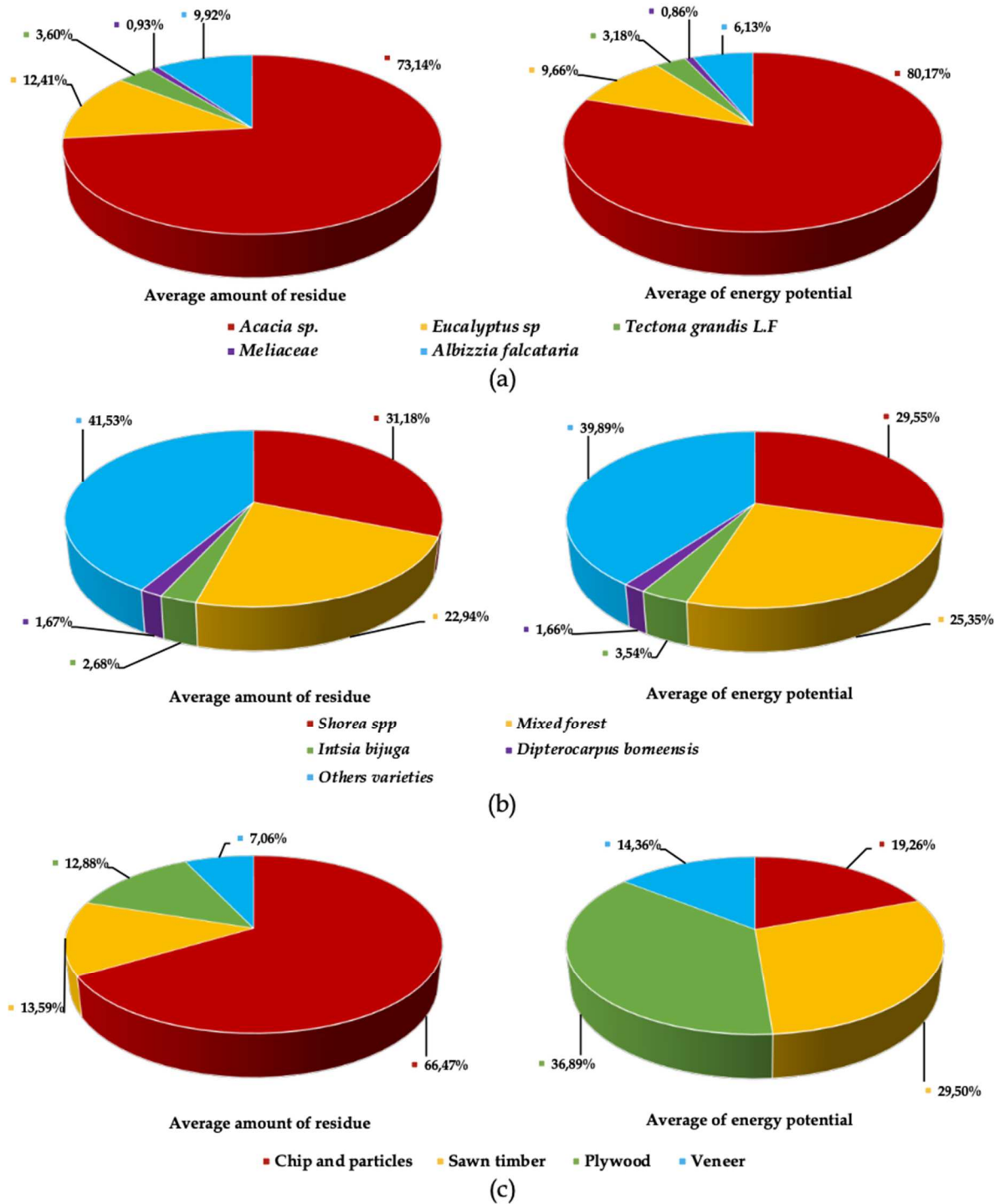
Nearly, 50% of the covered land area in Indonesia is forest, which means the total forest production around 40 million tonnes in 2020 (Statistics Indonesia, 2021). It has a great opportunity to create a sustainable bioenergy program from the primary residue in harvesting and extraction of logging activities, and timber manufacturing residue as secondary residue sources. From 2011-2019, the forest residue generated over 7.5 million tonnes of logging residue and 0.8 million tonnes of timber processing. Those can generate an energy potential of about 59 PJ and 5 PJ logging activities and wood processing. These results have a similar estimation value for the annual forest residue from prior research around 7.3 million tonnes,

1 can produce 48 PJ of energy (Dani and Wibawa, 2018). In the recent decades, the forest residue  
2 production has reached 3.7 million tonnes, equivalent to 15.64 PJ (Prastowo, 2011).

3 Fig. 5 illustrates the relationship between the quantity of forest residue and its energy  
4 potential in each group. In the industrial forest production sector, the total residue production  
5 of *Acacia* sp. reached 5.5 million tonnes. It almost generated 100% of its energy potential,  
6 equivalent to over 3400 MW per year. Whereas in the natural forest production sector, *Shorea*  
7 spp ranked first place with with the residue production of nearly 0.7 million tonnes,  
8 equivalent to producing 3.28 PJ of energy. In general, the quantity of wood residue is  
9 influenced by the physical properties of wood (e.g., density and moisture content and logging  
10 methods (e.g., woodcutting technique, wood fall direction and handling management). But,  
11 the environmental conditions, such as soil type, rainfall, temperature, and wind velocity, also  
12 play a significant factor in determining the quality and quantity of timber. For example,  
13 *Acacia* sp. is one of wood varieties that can vegetate in the infertile soil area and spread all  
14 over Indonesia due to its high environmental tolerance characteristics. The bulk of *acacia*  
15 (89.3%) is superior compared to *eucalyptus* (82.1%). The *Acacia* plantation generated a higher  
16 biomass density and more potential as a bioenergy source because it can be applied in various  
17 technology conversions.

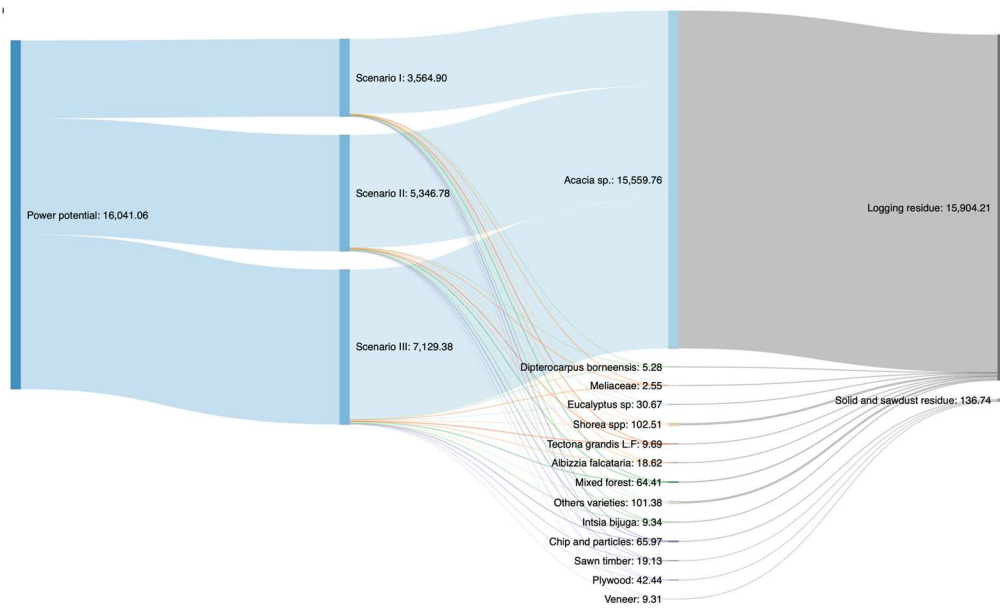
18 Generally, timber processing residue, such as solid and sawdust, is utilized as traditional  
19 energy for cooking and heating in the households and small industries. In Indonesia, over  
20 60% of wood processing residue is produced from chip and particle manufacturing and can  
21 generate around 0.889 PJ of energy potential, equivalent to 30 MW of power energy. Economic  
22 growth will affect the gradual increase of the wood processing residue production, for  
23 example in the fourth triwulan of 2020, chip and particle production increased 20% more than  
24 in the first triwulan, reaching 3.44 million tonnes. In the future, it is predicted that production  
25 capacity will gradually rise by approximately 10% to 30% due to management improvements  
26 to guarantee sustainability through policy, regulation, and infrastructure support.

27 Fig. 6 is the Sankey diagram of the power potential of forest residue, which illustrates that  
28 over 90% of power is generated by *Accacia* sp. compared to other products. The development  
29 potential of its varieties is supported by the fast harvesting cycle of around 5 or 6 years. It  
30 needs the stakeholders' awareness and support to guarantee the availability of feedstock for  
31 bioenergy purposes.



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**Fig. 5.** Residue production availability and energy potential of forest sectors in Indonesia, where (a) industrial forest production, (b) natural forest production, and (c) timber processing



**Fig. 6.** Sankey diagram: annual average power potential of forest sectors in Indonesia

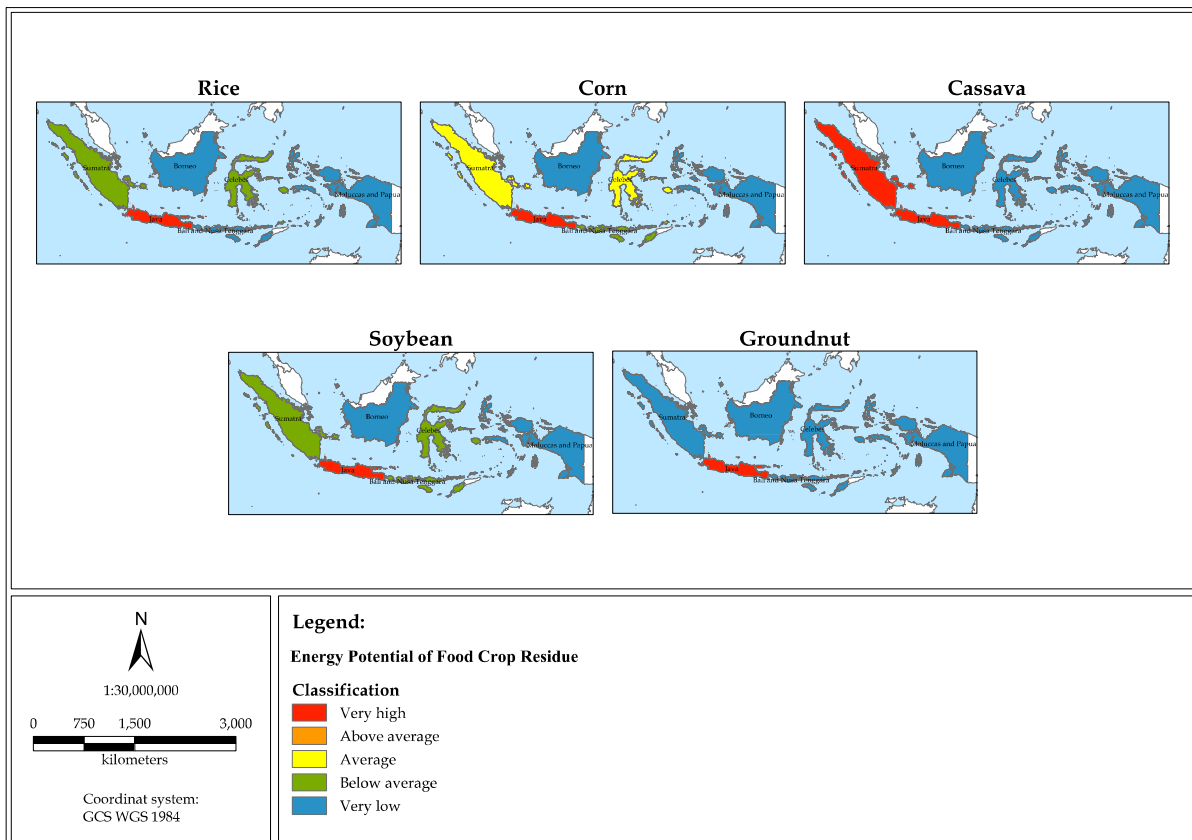
#### 4.3. Distribution of energy potential biomass residue

The GIS analysis is utilized to construct a geographical distribution of energy potential in each Island of Indonesia; it aims is to evaluate the feasibility of collecting and distributing the biomass residue. To construct a geographical distribution of energy potential, the zonal functional method is used by accumulating the total energy potential of agricultural and forest energy potential on each major Indonesian island with their respective attributes to map the data spatially. At the same time, the image classification of energy potential using maximum likelihood is classified into five classes (i.e., very high, above average, average, below average, and very low). The precise method for constructing a geographical distribution is shown in Appendix D.

Figs. 7 and 8 present the geographic distribution of energy potential from agricultural and forest residue. These finding describe that, Java Island has very high energy potential for its food crops and sugarcane as a plantation crop, compared to other islands. Java island is only dominated by food crops, while plantation crops are widely cultivated outside Java island. Contrastingly, Sumatra Island has a very high energy potential for four plantation crops, except sugarcane. The most significant plantation crop production is palm oil, and the cultivation area of palm oil in Indonesia is nearly 15 million ha. Sumatera's largest cultivation area is approximately 8 million ha and generates 22.46 PJ of energy potential. While Borneo island cultivates palm oil in one-fourth of its region, it has an average energy potential of about 11.65 PJ. Overall, palm oil is only cultivated in Sumatra, Borneo, and Papua Islands, but it is not cultivated on Java Island because the environmental capacity and water resources does not allow for its cultivation activities. Given forest residue production on Java Island,

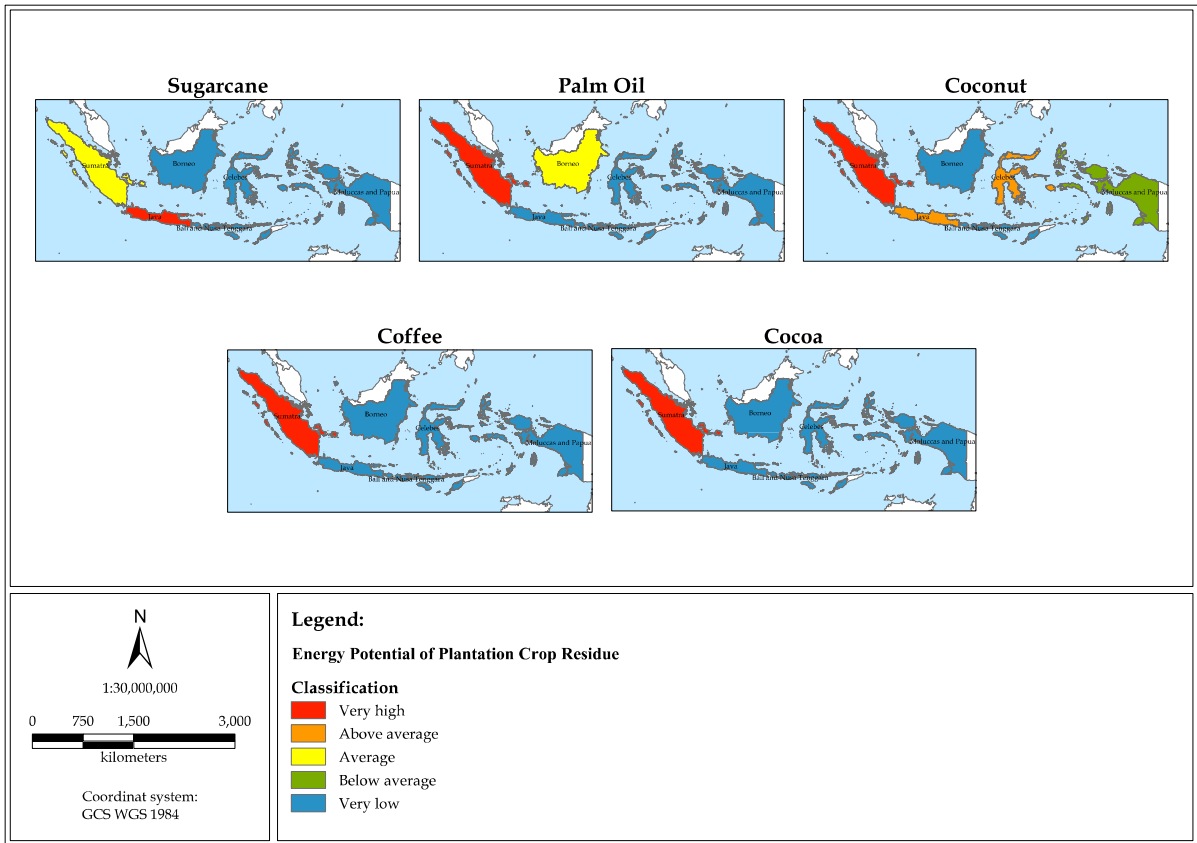
1 five out of ten wood varieties have a very-high category of energy potentials, i.e., *Tectona*  
 2 *grandis* L.F., *Meliaceae*, *Albizzia falcataria*, *Intisia bijuga*, and other varieties. While, on Sumatera  
 3 Island, five different types (i.e., *Acacia sp.*, *Eucalyptus sp.*, *Shorea spp*, *mixed forest*, and  
 4 *Dipterocarpus borneensis*) have a very-high category of energy production. For example, *Acacia*  
 5 *sp.* can produce 14.12 million tonnes of residue per year, generating nearly 32.42 PJ. There  
 6 could be a huge opportunity to develop the biomass power plant due to the feedstock  
 7 availability and the fact that the supplies are spread across Sumatera Island.

8 Fig. 9 shows that the largest production of timber manufacturing residue on Sumatera  
 9 island, which is produced by chip and particles, reached 10.64 million tonnes of residue and  
 10 will generate 0.13 PJ of energy. The other major timber processing products on Java Island are  
 11 sawn timber, plywood, and veneer, due to the most advanced wood processing industries  
 12 and the availability of facilities. In the future, it will need to improve other locations that have  
 13 great productivity from biomass by enhancing the quality of their supporting infrastructure  
 14 and technology to guarantee a sustainable supply chain and achieve the goals of green energy  
 15 production.



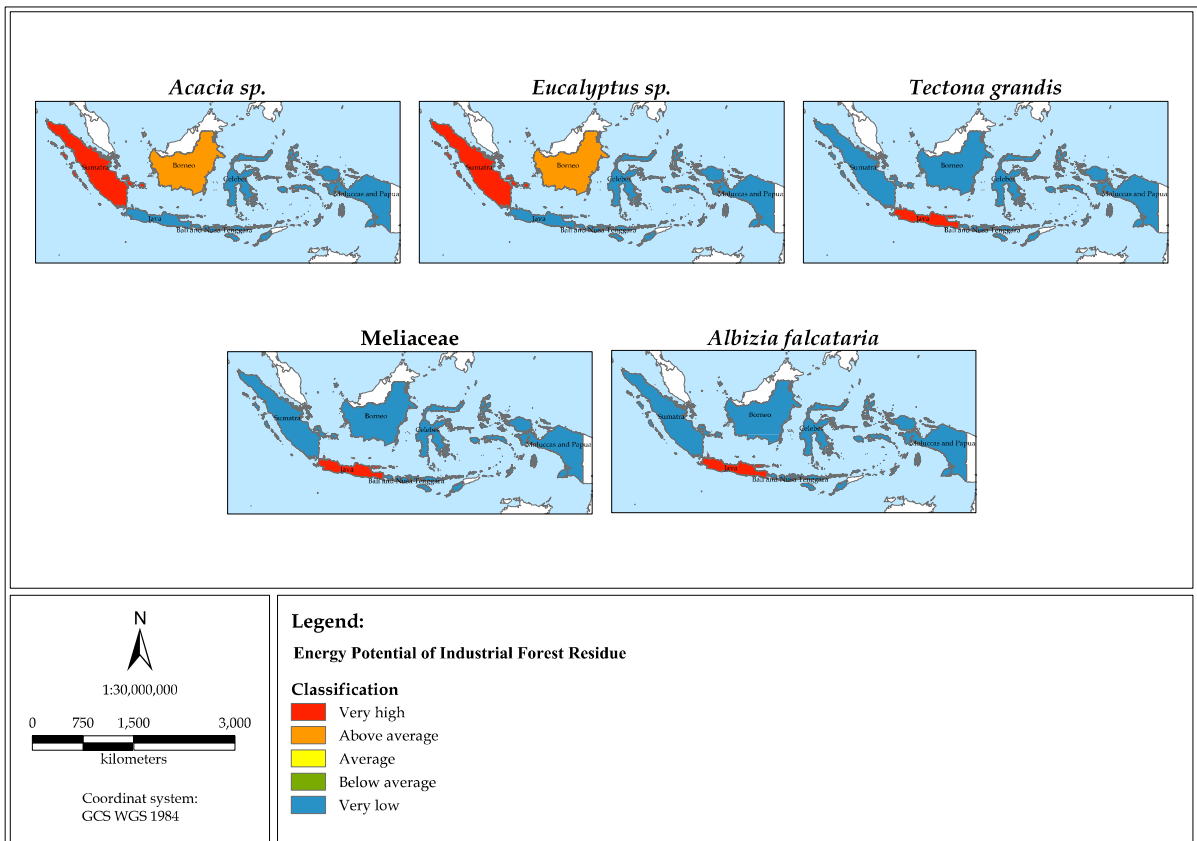
(a)

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(b)

Fig. 7. Geographical distribution of energy potential from agriculture residue in Indonesia, where (a) food crop and (b) plantation crop distribution

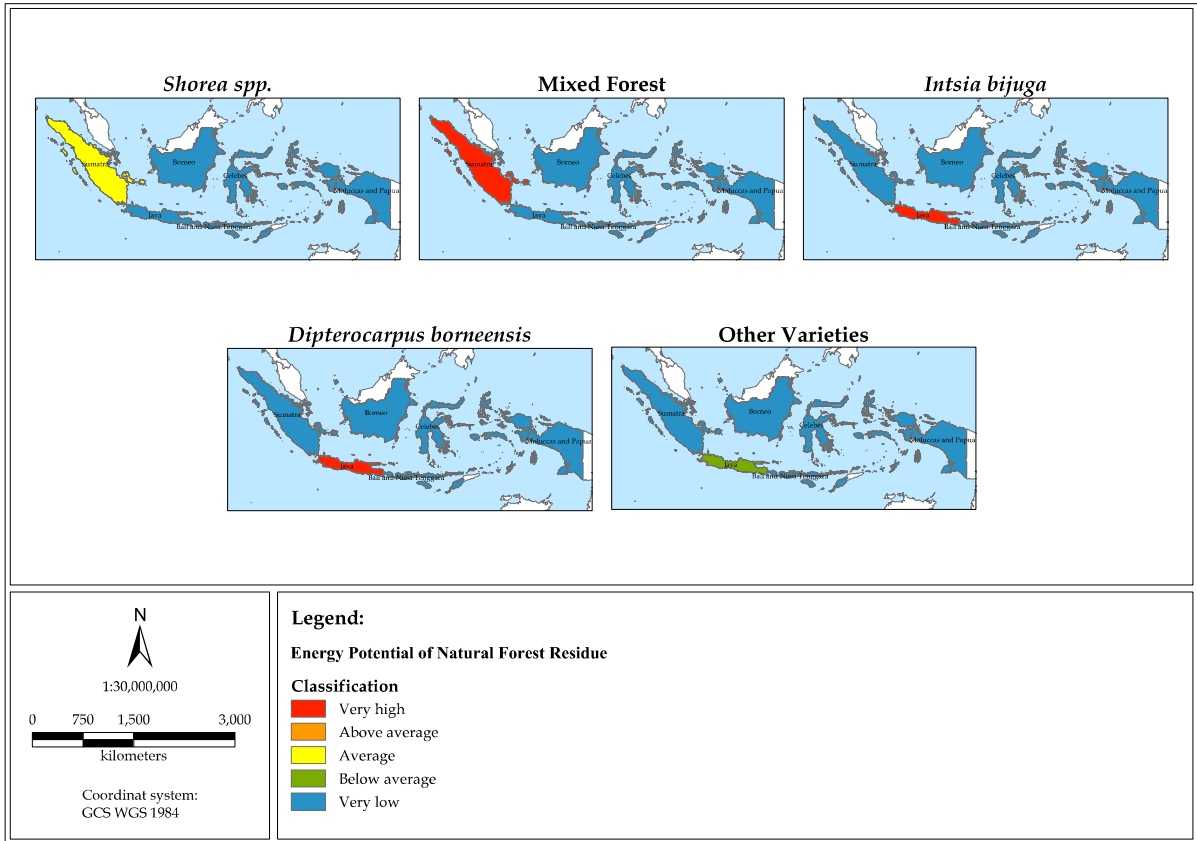


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(a)



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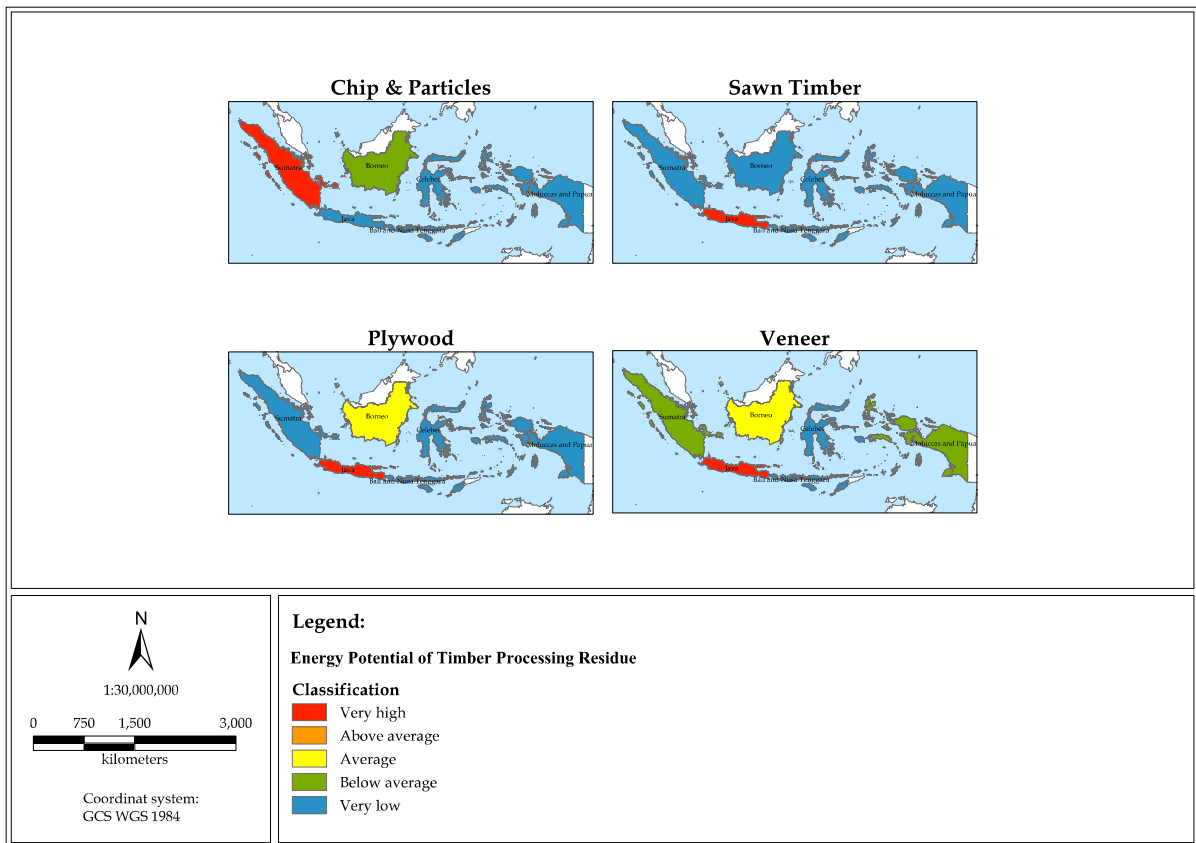
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(b)

**Fig. 8.** Geographical distribution of energy potential from forest residue in Indonesia, where (a) industrial forest production and (b) natural forest production





1  
2 **Fig. 9.** Geographical distribution of energy potential from timber processing residue in  
3 Indonesia

4 **5. Future perspective of Indonesian biomass residue utilization**

5 The utilization of food crops as energy sources has been abandoned since the last  
6 decade, similar to the traditional approach of burning the crop residue in post-harvest.  
7 Currently, the sustainable approach being applied refers to the Sustainable Development Goal  
8 (SDG) of utilizing biomass residue as an environmentally friendly raw material. The findings  
9 of this study reveal that Indonesia has a huge potential to use agricultural and forest residue  
10 to generate electricity. This study identified that the rice residue, such as straw and husk,  
11 produces a large volume every year throughout the year, and its availability and spatial  
12 distribution are even in all regions. The government's support has issued a national energy  
13 plan that presents some points for the application of biomass energy, i.e., 1) switching 10% of  
14 the capacity of coal power plants to biomass power plants in 2025; 2) guaranteeing the  
15 availability of Crude Palm Oil (CPO) as a national biofuel; 3) promoting non-edible crops as  
16 biomass energy; 4) increasing the quality and quantity of biomass potential surveys; 5)  
17 improving the quality of institutional production and distribution of biomass energy; 6)  
18 increasing the funding of research and development; 7) setting the price standard of biomass  
19 energy; and 8) industrialization of biomass energy. This paper also elaborates on the global



1 approach to converting the biomass residue into a biorefinery, which incorporates the concept  
2 of sustainable use of bio-based carbon. To establish the concept, the practical implications  
3 require appreciation from stakeholders throughout the value chain, from residue  
4 management, production, and market share. In this case, the main stakeholder is the farmer,  
5 who has a vital role in guaranteeing the sustainability of the raw material, while the  
6 government provides the facilities supporting it, such as policy and regulation, infrastructure,  
7 an integrated cooperation concept, and market share.

8 From a social-economic perspective, biomass residue as a lignocellulosic resource must be  
9 promoted by simultaneous valorization as a new paradigm in rural areas. The farmers who  
10 produce the sustainable raw materials need some education and training to change their  
11 mindset and awareness to manage the biomass residue through the collection, storing, and  
12 distributing processes before energy production in the biorefinery. In Indonesia,  
13 reorganizing the institutional framework of the village cooperative and optimizing the  
14 farmers' group role is a basic option to be done. The technology edorsment is an easier way  
15 to generate the biofuel. One of them is the densification process to convert biomass residue to  
16 pellets or briquettes, which is suitable for application in rural areas as an electricity source to  
17 implement the "Desa Mandiri Energi" program. On a small scale, pellets can be used for  
18 residential purposes, such as fuel for pellet stoves and electricity for pellet boilers, while in  
19 the industrial sector, pellets are a fuel for heat, steam, and power generation. For example, the  
20 utilization pellet from agricultural waste can be applied in the sugarcane industry as boiler  
21 heating and electricity. In general, pellets have advantages compared to unprocessed biomass  
22 or residue, i.e., 1) high energy content, 2) high density, 3) reduced operational cost for  
23 handling, transport, and storing, and 4) simple technology production, which requires  
24 minimum maintenance (Tumuluru, 2011). To realize its purpose on a commercial scale,  
25 strengthening the residue supply chain and infrastructure, such as warehouses, harvesting  
26 machinery, pellet machine production, and transportation networking, is needed. Moreover,  
27 manufacturing pellets in large quantities requires a substantial capital cost to set up the  
28 machinery and technology. For instance, the total total investment cost to produce 6 tons per  
29 hour of pellet is nearly 2.2 million US dollars (S. Mani et al., 2006). But the application of  
30 mobile pellet can be a simple solution in rural areas due to the fact that it can reduce feedstock  
31 and drying costs by removing the need to harvest expensive feedstocks in an area when cheap  
32 feedstocks are plentiful in another area (Jacobson et al., 2021). To produce a tonne of wood  
33 pellet, 1.6 tonnes of *Accacia sp.* residue (trunck and branch) is needed as a raw material  
34 (Saosee et al., 2020), and the LHV of *Accacia sp.* pellet is 18.63 MJ/kg (Duong et al., 2022).

1 According to the findings of this study, the annual production of *Accacia* sp. residue reached  
2 3,48 million tonnes, pellets were produced at a rate of 2,17 million tonnes per year, and an  
3 energy potential of approximately 64.8 PJ, equivalent to 449.9 MW of electricity power  
4 potential, was generated. While annual rice straw pellet production has a potential energy  
5 potential of 552.31 PJ, which is equivalent to 5753,24 MW of electrical power. It is assumed  
6 that the densification rice straw pellet method requires no additional water to produce 88.1%  
7 of yield and the LHV is 10.1 MJ/kg (Ishii and Furuichi, 2014). Considering the potential of  
8 agricultural and forest residue, the energy conversion facilities' development is necessary to  
9 increase the efficiency of production of the residue pellets by observing the analysis of social,  
10 economic, and environmental factors.

11 In correlation to environmental issues, the Indonesian commitment to reduce GHG  
12 emissions by 26% in 2020 and 29% in 2030 amounts to approximately 314 million tonnes of  
13 CO<sub>2</sub>, which means the energy sector has been able to reduce nearly 64.4 million tonnes of CO<sub>2</sub>  
14 in 2020 (Dirjen EBTKE, 2020). While its value is far from the target in 2030, as the results of the  
15 scenarios prepared to achieve the goals, i.e., 1) optimalization of renewable energy application  
16 of 10.1 million tonnes of CO<sub>2</sub>; 2) energy efficiency of 16.7 million tonnes of CO<sub>2</sub>; 3) low-carbon  
17 fuel transition of 9.56 million tonnes of CO<sub>2</sub>; and 4) post-mining reclamation of 0.38 million  
18 tonnes of CO<sub>2</sub> . In the case of biomass energy acceleration, the two methods to contribute to  
19 environmental sustainability are: 1) optimalization of degraded lands to produce energy crops  
20 from non-edible plants; and 2) optimalization of integration residue to produce bioenergy. At  
21 present, a great hope is pinned on the synergy of food and energy security being grown jointly  
22 to realize environmental sustainability. The general concept of future perspective is illustrated  
23 10.

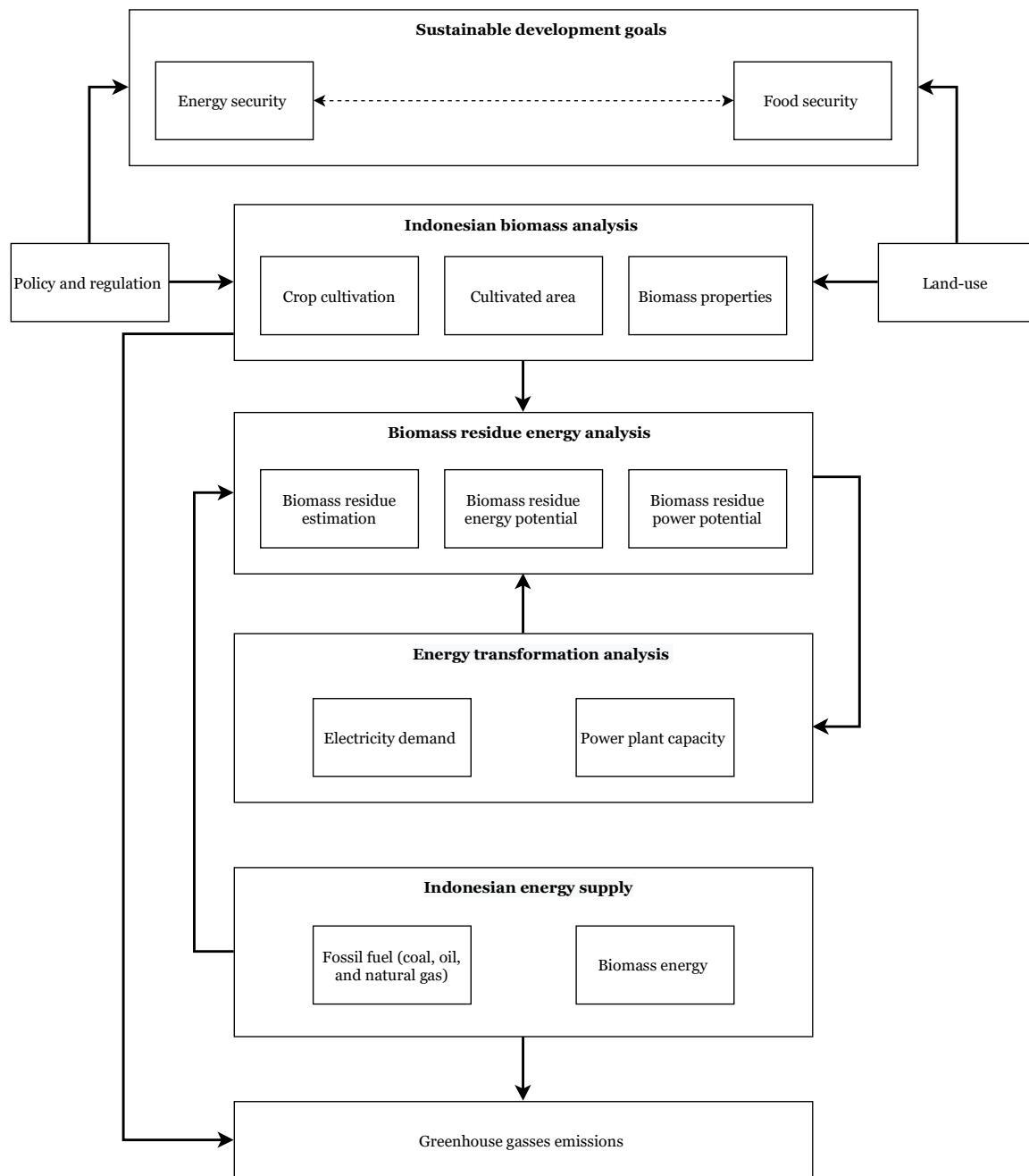


Fig. 10. Future perspective of biomass residue in Indonesia

## 6. Conclusions

The proposed method simply assessing the biomass potential of the agriculture and forest sectors. According to Indonesia's geography, it has abundant diversity and is also supported by climate and environmental conditions. It has affected biomass residue production, as a large quantity is created. The study estimated that agriculture and forest residue production is approximately 155.27 and 7.85 million tonnes of dry mass per year, respectively. The analysis shows that the highest share of energy potential is generated from rice residues such

1 as straw and husk from the agriculture sector and logging residue from Acacia sp. crops,  
2 considering they have been cultivated in all Indonesia locations. Java Island is the most  
3 productive to produce the main agriculture plant except palm oil, while Sumatra island is a  
4 more excellent producer of a few wood varieties such as Acacia sp., Eucalyptus, and mixed  
5 forest types. However, the unproductive area can be used support the raw material supply to  
6 guarantee sustainable bioenergy production.

7 The annual energy potential from agriculture, forest, and timber processing residues  
8 generated can reach 2822.29, 98.34, and 18.58 MW of fluidised bed combustion and generating  
9 turbine (C/GT) technology and 4181.17, 145.69, and 27.50 MW of combined cycle of gas and  
10 steam (C/GC) technology, respectively. Those could cover around 28% and 39% of the  
11 Indonesian electrical supply in 2019 (about 10565.92 GW). When it was applied to replace coal  
12 in power plants with biomass residue, the current consumption could save more than 38%  
13 annually. Although it may be challenging to realize in the short term, it is vital to assess the  
14 potential of biomass residue as bioenergy. In more detail, the monitoring and evaluation to  
15 recognize the sustainable energy from the guarantee of supply of raw materials, design of  
16 technology and supporting facilities, such as distribution and storage facility, policy and  
17 regulation and financing facility are a few points to realize the sustainable development of the  
18 state. The information created from this study is expected to help determine the energy  
19 potential of biomass residue in other sectors, for example, agro-industry, animal husbandry,  
20 aquatic sectors, and municipal solid waste, and will also contribute to the proper strategic  
21 planning of valorization technology and model to maximize the recovery of their residual  
22 materials. Thus, several issues can be further developed to optimize the Indonesian biomass  
23 residue, viz. 1) analyzing the properties of residue due to its strong impact on the  
24 sustainability of supply chain management, 2) environmental analysis of the biomass residue  
25 potential in all activities of collection, storage, transportation, and energy conversion, 3)  
26 technical and economic analysis of technology conversion and power plant from the  
27 engineering point of view, 4) social analysis of the biomass utilization development impact  
28 for the empowerment framework.

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## 11 Appendix

12 **Appendix A.** Type of agricultural residues and coefficient for the energy potential estimation  
 13 performed in this study

Subgroup of Agricultural Residue	Type of Product	Type of Residue	RPR*		Moisture (%)*		LHV (MJ/kg)*		Availability Factor (%)**		Reference
			Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	
Food crop residue	Rice	Straw	0.45 – 1.76	1.11	10.00 – 15.00	12.50	14.08 – 16.00	15.04	25.00 – 80.00	55.00	a,b,c,d
		Husk	0.20 – 0.26	0.23	9.60 – 13.30	11.45	12.90 – 19.93	16.42	25.00 – 80.00	55.00	
	Maize	Cob	0.27 – 0.86	0.57	7.70 – 8.70	8.20	12.60 – 18.40	15.50	20.00 – 60.00	40.00	c,d,e,f
		Stalk	2.00 – 2.27	2.14	15.00 – 16.80	15.90	15.50 – 18.50	17.00	20.00 – 60.00	40.00	
	Cassava	Stalk	0.06 – 0.40	0.23	15.00 – 20.00	17.50	13.10 – 16.99	15.05	20.00 – 80.00	50.00	g,h,i
	Ground nut	Shell	0.20 – 2.30	1.25	8.20 – 9.87	9.04	5.53 – 22.06	13.80	20.00 – 40.00	30.00	a,h
Plantation crop residue	Sugarcane	Bagasse	0.28 – 0.33	0.31	15.00 – 35.00	25.00	8.57 – 20.00	14.29	20.00 – 50.00	35.00	d,f,j,k,l,m
		Top and leaves	0.05 – 0.32	0.19	50.00 – 63.00	56.50	6.82 – 20.00	13.41	20.00 – 80.00	50.00	
	Coconut	Shell	0.16 – 0.25	0.21	8.00 – 16.00	12.00	16.48 – 20.15	18.32	20.00 – 40.00	30.00	g,h,i,n,o
		Husk	0.36 – 0.48	0.42	8.00 – 13.00	10.50	14.71 – 16.23	15.47	40.00 – 60.00	50.00	
	Palm Oil	Empty fruit brunch	0.17 – 0.43	0.30	8.81 – 14.00	11.41	6.71 – 16.44	11.58	10.00 – 50.00	30.00	g,i,o
		Shell	0.05 – 0.07	0.06	10.00 – 13.00	11.50	17.00 – 18.73	17.87	10.00 – 50.00	30.00	
		Fiber	0.13 – 0.15	0.14	10.00 – 13.00	11.50	12.22 – 16.19	14.21	10.00 – 50.00	30.00	
	Coffee	Husk	0.21 – 2.10	1.16	7.00 – 15.00	11.00	3.44 – 18.35	10.90	20.00 – 60.00	40.00	ij
	Cocoa	Pods	0.93 – 1.00	0.97	15.00 – 75.00	45.00	12.38 – 15.48	13.93	20.00 – 60.00	40.00	j,n

15 \* Based on the literature

16 <sup>a</sup>(Singh et al., 2008)

17 <sup>b</sup>(Iye and Bilborrow, 2013)

18 <sup>c</sup>(Okello et al., 2013)

19 <sup>d</sup>(Hiloidhari et al., 2014)

20 <sup>e</sup>(Chen et al., 2009)

21 <sup>f</sup>(Avcioglu et al., 2019)

- 1 <sup>g</sup>(Stich et al., 2017)  
 2 <sup>h</sup>(Sajakulnukit et al., 2005)  
 3 <sup>i</sup>(Wang et al., 2021)  
 4 <sup>j</sup>(Duku et al., 2011)  
 5 <sup>k</sup>(Uzair et al., 2020)  
 6 <sup>l</sup>(Gonzalez-Salazar et al., 2014)  
 7 <sup>m</sup>(Morato et al., 2019)  
 8 <sup>n</sup>(Kemausuor et al., 2014)  
 9 <sup>o</sup>(Shafie et al., 2012)  
 10 \*\* Based on the estimation in the field  
 11

12 **Appendix B.** Type of forest residues and the coefficient for the energy potential estimation  
 13 performed in this study

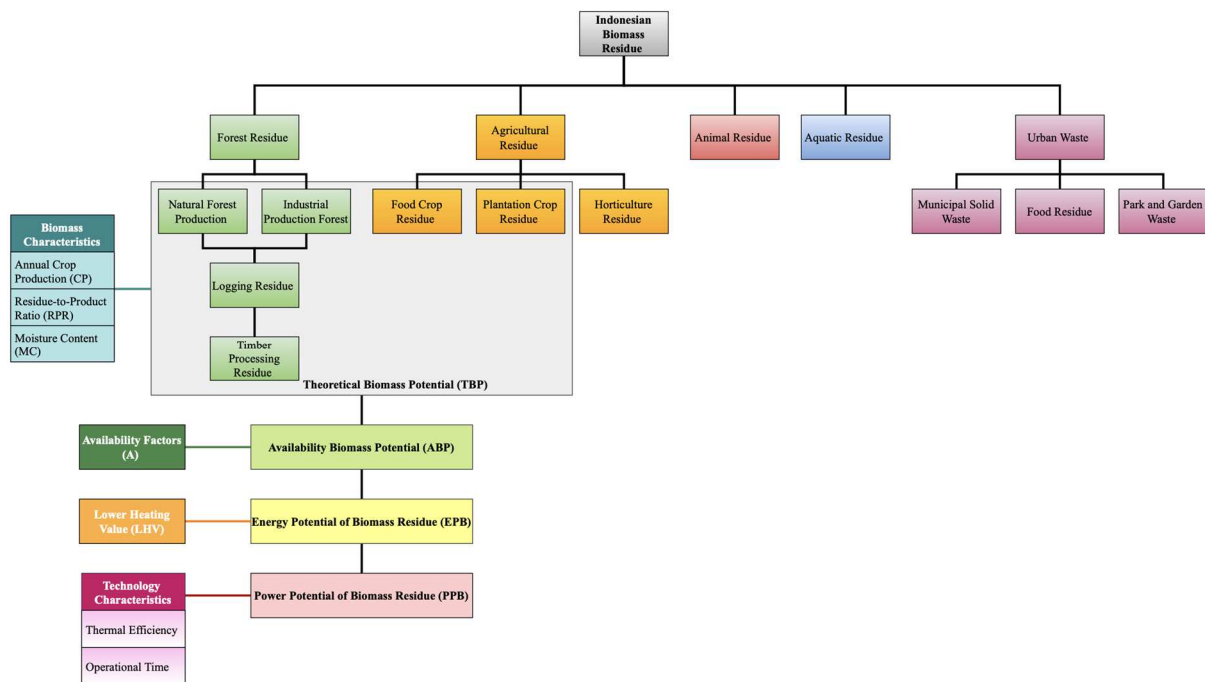
Group of Forest Residue	Sub Group of Forest Residue	Type of Product	Type of Residue	Density (kg m <sup>-3</sup> )* <sup>a</sup>		Moisture Content (%)* <sup>b</sup>		LHV (MJ/kg)* <sup>b</sup>		Availability Factor (%)* <sup>**</sup>	
				Range	Avg	Range	Avg	Range	Avg	Range	Avg
Logging processing	Industrial forest production	Acacia sp.	Logging residue	490.00 - 1000.00	745.00	50.00 - 50.00	50.00	8.00 - 8.00	8.00	42.00 - 79.00	60.50
			Logging residue	540.00 - 570.00	555.00	50.00 - 50.00	50.00	8.00 - 8.00	8.00	42.00 - 79.00	60.50
		Tectona grandis LF	Logging residue	480.00 - 850.00	665.00	50.00 - 50.00	50.00	8.00 - 8.00	8.00	42.00 - 79.00	60.50
			Logging residue	637.10 - 637.10	637.10	50.00 - 50.00	50.00	8.00 - 8.00	8.00	42.00 - 79.00	60.50
		Albizzia falcataria	Logging residue	230.00 - 640.00	428.00	50.00 - 50.00	50.00	8.00 - 8.00	8.00	42.00 - 79.00	60.50
			Logging residue	640.00 - 640.00	640.00	50.00 - 50.00	50.00	8.00 - 8.00	8.00	42.00 - 79.00	60.50
	Natural forest production	Shorea spp	Logging residue	380.00 - 1080.00	730.00	50.00 - 50.00	50.00	8.00 - 8.00	8.00	42.00 - 79.00	60.50
			Logging residue	703.00 - 703.00	703.00	50.00 - 50.00	50.00	8.00 - 8.00	8.00	42.00 - 79.00	60.50
		Intsia bijuga	Logging residue	840.40 - 840.40	840.40	50.00 - 50.00	50.00	8.00 - 8.00	8.00	42.00 - 79.00	60.50
			Logging residue	840.40 - 840.40	840.40	50.00 - 50.00	50.00	8.00 - 8.00	8.00	42.00 - 79.00	60.50
		Dipterocarpus borneensis	Logging residue	500.00 - 850.00	675.00	50.00 - 50.00	50.00	8.00 - 8.00	8.00	42.00 - 79.00	60.50
			Logging residue	611.10 - 611.10	611.10	50.00 - 50.00	50.00	8.00 - 8.00	8.00	42.00 - 79.00	60.50
Wood processing	Timber processing	Chip and particles	Solid and sawdust residue	380.00 - 380.00	380.00	10.00 - 50.00	30.00	6.00 - 15.00	10.50	25.00 - 70.00	47.50
			Solid and sawdust residue	470.00 - 470.00	470.00	30.00 - 30.00	30.00	12.00 - 12.00	12.00	25.00 - 70.00	47.50

Plywood	Solid and sawdust residue	620.00 – 620.00**	5.00 – 10.00	15.00 – 17.10	25.00 – 47.50
Veneer	Solid and sawdust residue	440.00 – 440.00**	30.00 – 30.00 <sup>b</sup>	12.00 – 12.00	25.00 – 47.50

- 1 \* Based on the literature
- 2 <sup>a</sup>(ICRAF Database, 2021)
- 3 <sup>b</sup>(Mboumboue and Njomo, 2018b)
- 4 \*\* Based on the estimation in the field

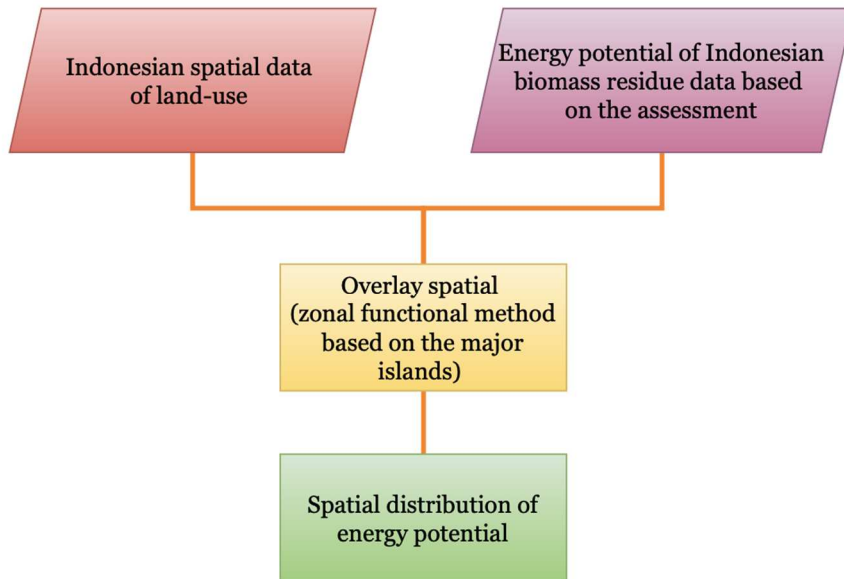
6 **Appendix C.** Flow diagram to calculate the energy and electrical potential of Indonesia  
7 biomass residue

8 The resources of Indonesian biomass residue can be grouped into five, i.e., forest residue,  
9 agriculture residue, animal residue, aquatic residue, and urban waste. In this study, two  
10 groups of biomass residue will be thoroughly analyzed, i.e., forest and agriculture residue.



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- 13 **Appendix D.** Methodology to construct an energy potential spatial distribution
- 14 The data sources to construct a geographical distribution of energy potential are:
- 15 a. Basic map of Indonesia at scale 1:40,000,000 from Geospatial Information Agency.
- 16 b. Digital land cover data and image results by LDCM (Landsat Data Continuity
- 17 Mission)/LSat 8 OLI coverage in 2019 resolution 30x30 m by Directorate General of
- 18 Forestry Plans and Governance Environment.

- 1 Based on the data assessment, the forest and non-forest land's accuracy value was obtained at
- 2 76.80%.



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