Preliminary Study of Fuelwood Properties in a Short-Rotation Tree, *Indigofera tinctoria* L., Planted in Indonesia

Denny Irawati,[a,*] Futoshi Ishiguri,[b] Ajidian Nugroho,[a] Andika Haryo Wicaksono,[a]
Dwiko Budi Permadi,[a] and Shinso Yokota,[b]

Indigofera tinctoria L. is known to produce economically valuable indigo dye. Recently, *I. tinctoria* has also been considered a potential species for establishing energy plantations because this species can rapidly produce large quantities of biomass. However, knowledge about its fuelwood properties is still limited. To optimize utilization of this biomass material as a source of energy, the fuelwood properties of this species were evaluated. In addition, the effect of radial growth rate on fuelwood properties in this species by mixed-effect modeling approaches were also evaluated. The productivity rate of above-ground biomass was found to be 7.4 tons ha^{-1} year $^{-1}$. The estimated average values in fresh weight, dry weight, moisture content, ash content, and carbon content were 7.4 kg, 3.7 kg, 53.4%, 0.90%, and 1.6 kg, respectively. According to the results of mixed-effect modeling, it is concluded that faster-growth characteristics of the tree did not always deteriorate the fuelwood properties of this species.

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Keywords: Above-ground biomass; Energy plantation; Tree diameter; Calorific value; Productivity

Contact information: a: Faculty of Forestry, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia;
b: School of Agriculture, Utsunomiya University, Utsunomiya 321-8505, Japan;
** Corresponding author: dirawati@ugm.ac.id*

INTRODUCTION

In the global energy crisis fueled by fossil energy consumption, alternative environmentally friendly, renewable energy sources are needed. Recently, biomass from fast-growing plant species (including both woody and non-woody plants) and biomass waste have been utilized as biofuel sources (Sedjo and Sohngen 2013; Bonifacino *et al*. 2021; Ju *et al*. 2022) and firewood, wood chips, or bio-pellets (Marsoem and Irawati 2016; Amoah *et al*. 2020; Irawati *et al*. 2020; Prasetyadi and Sutapa 2023). The national program for steam power plants in Indonesia requires biomass of 60 million tons/year; however, currently only 10.5 million tons/year has been fulfilled. One of the fulfillment scenarios, in addition to the utilization of forestry and agricultural waste, is the development of energy plantations. Such plantations can be established using fast-growing tree species. Characteristics of the species for fuelwood production should be rapid growth, high wood density, nitrogen-fixing abilities, high calorific value, burning without sparks or toxic smoke, low sulfur content, low ash content, easy splitting, and quick drying (Kerckhoffs and Renquist 2013). To date, several fast-growing trees have been selected for establishing the plantation for fuelwood production: *Populus* spp., *Eucalyptus* spp., *Acacia* spp., *Calliandra* spp., and *Gliricidia* spp. (Hinchee *et al*. 2011; Marsoem and Irawati 2016;

Prima and Hartono 2018; Amoah *et al*. 2020). However, many other tree species still have high biomass potential, but their energy characteristics are unknown. For the optimal utilization of biomass materials as a source of energy, a thorough knowledge and understanding of their energy characteristics are necessary.

Indigofera tinctoria L. is a fast-growing tree species with many branching characteristics. This species produces economically valuable indigo dye, which was used even thousands of years ago (Splitstoser *et al*. 2016; Agustarini *et al*. 2022; Lopes *et al*. 2022). This species is also an important prairie legume (Schrire 2013), with many benefits, such as an ornamental plant, soil cover, shade plant, green humus cover, and erosion control (Marquiafável *et al*. 2009). They are also used for their medicinal properties (Pan *et al*. 2010; Gerometta *et al*. 2020). Recently, *I. tinctoria* has been considered a potential species for energy plantation because this species can rapidly produce large quantities of biomass per unit area as well as the easy establishment and regeneration of plantation. If this species can be utilized for biomass production, then it can be a multipurpose species for indigo dye production from leaves and biomass energy from wood. However, the information regarding the energy quality of the biomass from this species is still limited.

In this study, the above-ground biomass and fuelwood properties were evaluated for 20-month-old *I. tinctoria* trees planted in Indonesia to assess the species as a new candidate for biomass energy production in the tropics. In addition, the effect of radial growth rate on fuelwood properties in this species by mixed-effect modeling approaches were evaluated. Finally, based on the results, the prospects of biomass energy production by this species were discussed.

EXPERIMENTAL

Materials

A plantation of 20-month-old *Indigofera tinctoria* L. used in the present study was located in Gadjah Mada University forests (Wanagama), Gunungkidul, Yogyakarta, Indonesia (110° 53′ E and 7° 90′ S; Fig. 1). The average annual temperature and precipitation in the University forests are about 27 °C and 1200 to 1900 mm year^{-1}, respectively (Fig. 1). The soil type is lithosol and entisol, with a maximum solum thickness of 20 cm. The trees were initially planted with a spacing of 3 × 1 m^2 in a plot (0.05 ha). A total of 166 trees were grown on the plantation. No silvicultural treatments, such as thinning, pruning, and fertilizing, were applied in the plantation before harvesting trees for this experiment.

Methods

Measurements of above-ground biomass

Stem diameter at 50 cm above the ground was measured by simple random sampling for randomly selected 66 trees in the plantation with spacing = 3 by 1 m. The results for the mean (μ) and standard deviation (σ) of the stem diameter in 66 selected trees was 4.74 ± 1.77 cm (Fig. 2). Based on the results, 12 trees in total for the three diameter classes ($Ø < 2.98$ cm [suppressed]; $2.99 < Ø < 6.50$ cm [medium]; and 6.51 cm $< Ø$ [dominant]) were harvested to measure the total weight of the above-ground biomass.

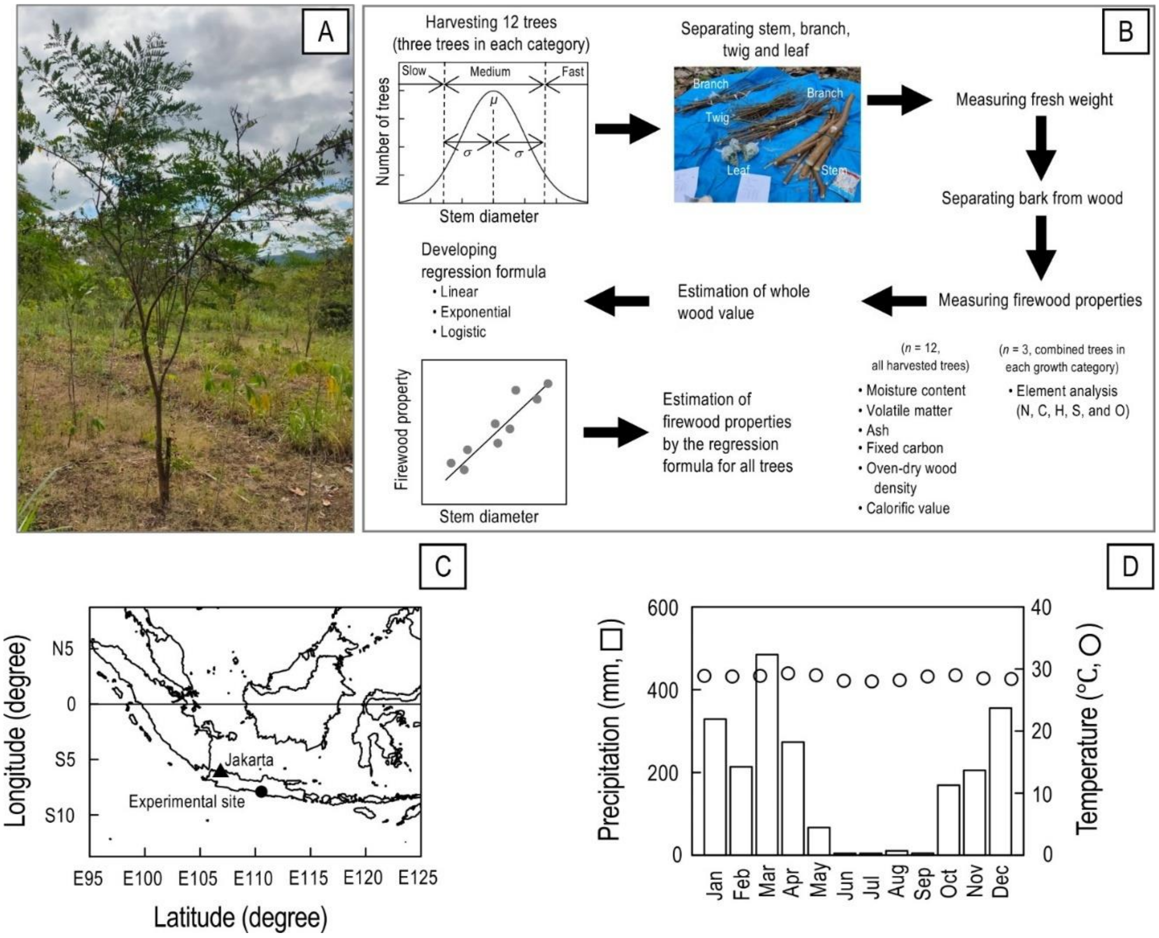

Fig. 1. A photograph of 2-year-old *Indigofera suffruticosa* trees (A), schematic diagrams of this experiment (B), map of plantation site (C), and climatic data of the plantation site (D).
Note: Climatic data (mean monthly temperature and total precipitation) was collected in Playen, Gunung Kidul, Yogyakarta, Indonesia (the nearest metrological station from experimental site) at 2020 (provided from Serayu Opak Large River Basin Organization, Indonesia)

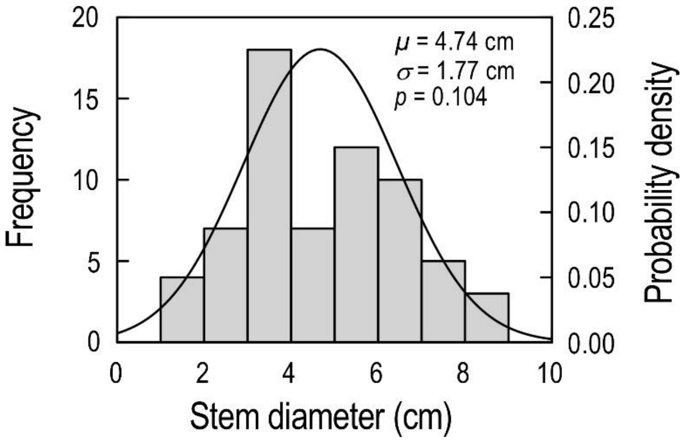

Fig. 2. Frequency distribution of stem diameter at 50 cm above the ground; Note: Number of trees = 66, μ, mean; σ, standard deviation; p, probability of Shapiro-Wilk test

The above-ground biomass was categorized into four components (leaves, twigs, branches, and stems), according to Hakkila (1989). Then, the fresh weight of these components was determined with an accuracy of 0.1 kg. To determine the dry weight of these components without drying, moisture content (MC, wet basis) was measured for sub-samples of each component. Approximately 2.0 g of sub-samples were weighed immediately after collection and oven-dried at 103 ± 2 °C until a constant weight was achieved. The final weight was used to calculate the MC. Calculated MC in each sub-sample was applied to estimate the dry weight of the components.

Fuelwood properties

The following properties were measured as fuelwood properties in the present study: MC, oven-dry wood density (WD_{OD}), volatile matter contents (VMC), ash contents (AC), fixed carbon contents (FCC), calorific value, and element composition (carbon [C], hydrogen [H], nitrogen [N], sulfate [S], and oxygen [O]). The fuelwood properties were measured in xylem and bark in each above-ground component category. Thus, values of fuelwood properties in each above-ground component category were calculated as area-weighted values based on the measured values in xylem and bark. In addition, part of the leaf is not included in the calculation as a source of energy because besides the leaf only containing a small amount, generally, the MC of the leaves on broadleaf species is high with a low caloric value (Hakkila 1989; Ngangyo-Heya *et al*. 2016; Mudryk *et al*. 2021), and the leaves of the *I. tinctoria* are generally used for dyes, animal feed, and medicines.

A small specimen (approximately 2 g with different shapes depending on the samples) for measuring WD_{OD} was obtained from each sample. The samples were dried in an oven at 103 ± 2 °C and weighed every 2 hours until constant weight. The oven-dried samples were then coated with paraffin, and then the oven-dry volume of the coated samples was measured by the water displacement method. The WD_{OD} was determined by dividing the values of oven-dried weight by oven-dried volume measured by the water displacement method.

The VMC, AC, and FCC in each sample were determined based on ASTM D1762-84 (2007); ASTM D1102-84 (2001); ASTM D3172-89 (2002), respectively. For determining the VMC, 2 g of oven-dry samples were heated using a furnace (FD 1530M, Thermolyne, USA) with an increasing rate of 100 °C/min until 950 °C within 15 min. Then, the sample was cooled in the desiccator before recording the final weight. The difference between the final weight and the initial dry weight of the sample was defined as the VMC. The AC was determined as the residue remaining after heating by the following temperature program: 100 °C min^{-1} increase to 600 °C and then kept for 6 h. The FCC was calculated by using the following Eq. 1:

$$\text{FCC}\ (\%) = 100 - (\text{MC} + \text{VMC} + \text{AC}) \tag{1}$$

One gram of each sample was placed in a semi-automatic oxygen bomb calorimeter (C-200, IKA, Germany) to determine calorific value by ASTM D2015-96 (1996). However, during the process in oxygen bomb calorimeter, the heat loss cannot be eradicated completely and hence is a possible source of error (Shehab *et al.* 2022).

Ultimate analysis to determine the CHNS elemental contents was performed using a FlashSmart analyzer (Thermoscientific, USA). During the process O is used for complete reaction of C, H, N, and S; therefore, O cannot be counted directly (Shadangi *et al*. 2023). Oxygen is counted indirectly as the remaining element to complete up to 100%. Using the carbon contents (%) and estimated dry weight, carbon contents (CC, kg) in a tree were calculated. Ultimate analysis is valuable tool to determine the identities and proportions of elements in a material.

Statistical analysis

All statistical analyses were conducted using R software (R Foundation for Statistical Computing, version 4.2.2, Vienna, Austria). To estimate above-ground biomass and fuelwood properties of measured trees (66 trees), the following three regression formulae (based on linear, exponential, and logistic functions) were developed using stem diameter (D) as an explanatory valuable:

$$y = a \bullet D + b \tag{2}$$

$$y = a \bullet \mathrm{e}^{(D \bullet -b)} \tag{3}$$

$$y = a / 1 + b\ \mathrm{e}^{(-c \bullet D)} \tag{4}$$

The estimated values were calculated by these formulae, and then mean absolute error (MAE) was calculated. The regression formula showing the minimum MAE value was regarded as the best regression formula of the property. In addition, in cases where the MAE values were similar among formulae, the simpler formula was selected.

To evaluate the effects of radial growth rates on fuelwood properties, the following intercept-only linear mixed-effect model (Nezu *et al*. 2022) was developed using the “lmer” function in the lme4 package (Bates *et al*. 2015),

$$y_{ij} = \mu + Growth_i + e_{ij} \tag{5}$$

where y_{ij} is the measured value of the j^{th} individual tree of the i^{th} growth category, μ is the fixed-effect parameter, $Growth_i$ is the random-effect parameter of the growth category i, and e_{ij} is the residual. The variance component ratio of the growth category was also calculated as the ratio of the variance of the category to the total variance (Nakagawa and Schielzeth 2010).

RESULTS AND DISCUSSION

Results

Figure 2 shows the frequency distribution of stem diameter at 50 cm above ground of *Indigofera tinctoria* L. The stem diameter of the *I. tinctoria* tree ranged from 1.85 to 8.60 cm, and the mean and standard deviation was 4.74 and 1.77 cm, respectively (Fig. 2). The distribution of these diameters could be regarded as the normal distribution because the p-value ($p = 0.104$) in the Shapiro-Wilk test exceeded 0.05.

Statistical values of above-ground biomass and fuelwood properties are listed in Table 1. The average fresh weight of the stem, branch, twig, and leaf were 5.0, 1.6, 0.8, and 0.4 kg, respectively. The average total fresh weight of the plants was 7.8 kg, while the woody part (7.3 kg) that could be used for energy occupied over 90% of the total fresh weight of the plants. The dry weight estimated by MC and the fresh weight of samples was 2.6 kg in the stem, 0.7 kg in the branch, 0.4 kg in twigs, and 0.1 kg in leaves. The mean value of total wood was 3.6 kg.

Table 1. Statistical Values of Fuelwood Properties from 12 Sample-Harvested Trees

Property	Stem	Branch	Twig	Total Wood	Leaf
VM (%)	81.96 ± 0.39	81.99 ± 0.51	79.85 ± 0.78	81.76 ± 0.28	–
Ash (%)	0.81 ± 0.16	0.82 ± 0.51	1.78 ± 0.43	0.90 ± 0.19	–
FC (%)	17.24 ± 0.50	17.18 ± 0.62	18.37 ± 0.90	17.34 ± 0.43	–
WD_{OD} (g/cm^3)	0.68 ± 0.06	0.67 ± 0.08	0.73 ± 0.15	0.69 ± 0.05	–
CV (kJ g^{-1})	16.47 ± 0.71	16.17 ± 0.63	16.25 ± 0.50	16.39 ± 0.49	–
CC (kg)	1.10 ± 0.81	0.31 ± 0.29	0.22 ± 0.18	1.61 ± 1.40	–

Note: FW, FRESH weight; DW, dry weight; MC, moisture content; VM, Volatile mater; FC, fixed carbon; WD_{OD}, fuelwood density including wood and bark at oven-dry condition; CV, calorific value; CC, carbon contents. Dashes (–) indicate no available data

Table 1 also provides the fuelwood properties of *I. tinctoria*. The mean MC showed almost the same values (50% to 60%) in stems, branches, and twigs, while the MC in leaves had higher values (72.6%) than the other four components. The mean VMC, AC, and FCC in total wood were 81.76%, 0.90%, and 17.34%, respectively. The AC in twigs was relatively higher than the other two components. In contrast, the WD_{OD} of the twig (0.735 g cm^{-1}) was higher than the others (0.678 g cm^{-1} in stems and 0.672 g cm^{-1} in branches). Although the components (stems, branches, and twigs) differed, the calorific value of the *I. tinctoria* was almost the same, being about 16.5 kJ g^{-1}. The estimated CC showed the highest value in stems (1.1 kg), followed by branches (0.3 kg) and twigs (0.2 kg). The average CHNS/O elemental content in *I. tinctoria* tree biomass is presented in Fig. 3. The mean values were 44.52% in C, 6.17% in H, 0.59% in N, 0.00% in S, and 48.71% in O, respectively. To estimate the above-ground biomass and fuelwood properties in 66 trees, regression formulae with an explanatory valuable of stem diameter based on linear, exponential, and logistic functions were developed (Table 2, Table S1). Through selection of the formula using MAE values (Table S2), a regression formula based on logistic function was selected for property related to above-ground biomass (fresh weight, DW, CC), and a linear regression formula was selected for MC, AC, and FC (Table S2). For VM, WD_{OD}, and CV, the p-value of the parameter exceeded 0.05, or formula was not obtained (Table 2, Table S1). Through using the selected formula, above-ground biomass and fuelwood properties were estimated. Mean values of estimated values in fresh weight, DW, MC, AC, and CC were 7.4 kg, 3.7 kg, 53.4%, 0.90%, and 1.6 kg, respectively (Fig. 4).

Table 3 shows fixed-effect parameters, random effects, and variance components of the intercept-only mixed-effect model for fuelwood properties. In fresh weight, DW, CV, and CC, the model was not obtained because the p-value in the fixed-effect parameter exceeded 0.05 or the model was not converged. The higher variance component ratio was found in MC (83.5%), AC (86.9%), and FC (58.4%).

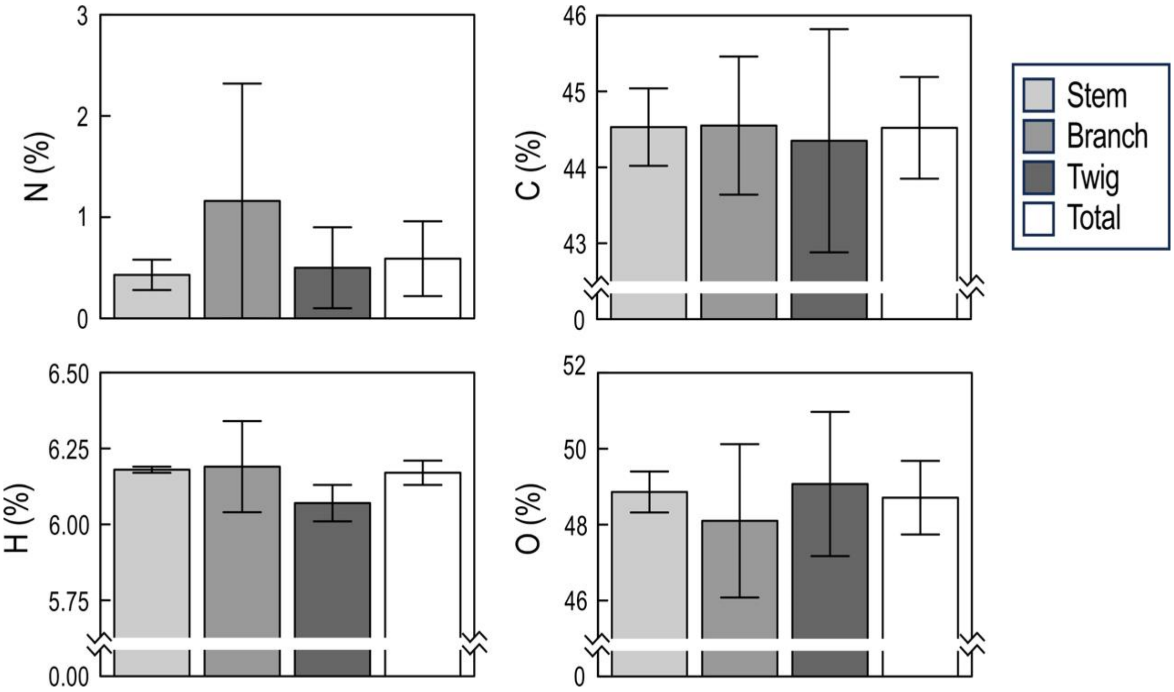

Fig. 3. Results of Element Analysis of Sample Trees. Note: N, nitrogen; C, carbon; H, hydrogen; O, oxygen. Three samples in each radial growth category were combined to determine elemental components.

Discussion

General fuelwood properties

Indigofera tinctoria L. is a species that is adaptive to marginal land and can naturally regrow after being harvested (Agustarini *et al*. 2022). In the present study, the mean value of the estimated dry weight of above-ground biomass in a tree was 3.7 kg. Thus, the productivity rate in this study was 7.4 tons ha^{-1} year $^{-1}$ (tree planting density = 3330 trees ha^{-1} [initial spacing = 3 by 1 m]; 3.7 by 3330 kg ha^{-1} 20 months $^{-1}$). This value is in the range of willow (*Salix* spp.) biomass yield (5.7 to 11.4 tons ha^{-1} year $^{-2}$) from the previous study (Stolarski *et al*. 2019). However, it has been reported by the U.S. Department of Energy and others that a productivity rate of 8 to 10 dry tons acre^{-1} year $^{-1}$ (= 19.8 to 24.7 tons ha^{-1} year $^{-1}$) will be required for the long-term feasibility of renewable energy production (Hinchee *et al*. 2011). Thus, the productivity of *I. tinctoria* in this study is still only half of the long-term feasibility of renewable energy production in the U.S. Further research is needed to increase the productivity rate by some silvicultural treatments, such as an increase of initial planting spacings and others.

In addition, increasing the amount of biomass up to 2 to 5 times can be done by applying silvicultural activities, such as genetically improving the plants and optimizing land growth conditions (Hinchee *et al*. 2011). Thus, tree breeding programs for above-ground biomass production in this species are also needed to increase biomass production.

Table 2. Parameter Estimates of Selected Regression for Estimating Fuelwood Properties by Stem Diameter of Trees

Property	Formula	Parameter											
		A				*B*				*c*			
		Estimates	SE	t-value	p-value	Estimates	SE	t-value	p-value	Estimates	SE	t-value	p-value
FW	Logistic	22.5752	3.7701	5.988	0.001	118.9042	34.0442	3.493	0.013	0.79559	0.1069	7.443	<0.001
DW	Logistic	12.10698	1.77221	6.832	<0.001	169.83683	40.23221	4.221	0.006	0.83370	0.08897	9.389	<0.001
MC	Linear	–2.854	0.490	–5.828	0.001	66.887	2.450	27.297	<0.001				
VM	–												
Ash	Linear	–0.098	0.016	-6.071	0.001	1.362	0.081	16.870	<0.001				
FC	Linear	0.190	0.058	3.310	0.013	16.446	0.288	57.160	<0.001				
WD$_{OD}$	–												
CV	–												
CC	Logistic	5.1947	0.7027	7.392	<0.001	175.2857	46.0408	3.807	0.009	0.8546	0.0923	9.259	<0.001

Note: SE, standard error; FW, fresh weight of above ground biomass except for leaves; DW, dry weight of above ground biomass except for leaves; MC, moisture content; VM, Volatile mater; C, carbon content of above ground biomass except for leaves; FC, fixed carbon; WD$_{OD}$, fuelwood density including wood and bark; CV, calorific value; CC, carbon contents of above ground biomass except for leaves. Dashes indicate that significant ($p < 0.05$) parameter estimates were not obtained in three formulae (linear, exponential, and logistic).

Table 3. Effects of Tree Radial Growth Rate on Fuelwood Properties

Property	Fixed-effect Parameters				Random Effects			Variance Component		
	Estimates	SE	t-value	p-value	Dominant	Medium	Suppressed	Category	Residual	Ratio
FW	7.336	3.862	1. 900	0.198	–	–	–	–	–	–
DW	3.642	2.055	1.773	0.218	–	–	–	–	–	–
MC	53.42	3.39	15.750	0.004	–5.152	–0.659	5.810	32.375	6.419	83.5
VM	81.76	0.11	737.40	< 0.001	–0.065	–0.017	0.083	0.014	0.067	17.7
Ash	0.900	0.118	7.640	0.0167	0.006	–0.168	–0.044	0.040	0.006	86.9
FC	17.34	0.23	75.840	< 0.001	0.090	0.277	0.073	0.127	0.090	58.4
WD_{OD}	0.6862	0.0170	40.480	0.001	0.0033	–0.0012	–0.0021	8.57e-05	2.33e-03	3.5
CV	–	–	–	–	–	–	–	–	–	–
CC	1.630	0.918	1.776	0.218	–	–	–	–	–	–

Note: SE, standard error; FW, fresh weight of above ground biomass except for leaves; DW, dry weight of above ground biomass except for leaves; MC, moisture content; VM, Volatile mater; FC, fixed carbon; WD_{OD}, fuelwood density including wood and bark at oven-dry condition; CV, calorific value; CC, carbon contents of above ground biomass except for leaves. Bars in fixed-effect parameters indicate that the formula was not converged. Dashes in random effects and variance component indicate that the values were not obtained because *p*-value of the fixed-effect parameters exceeded 0.05.

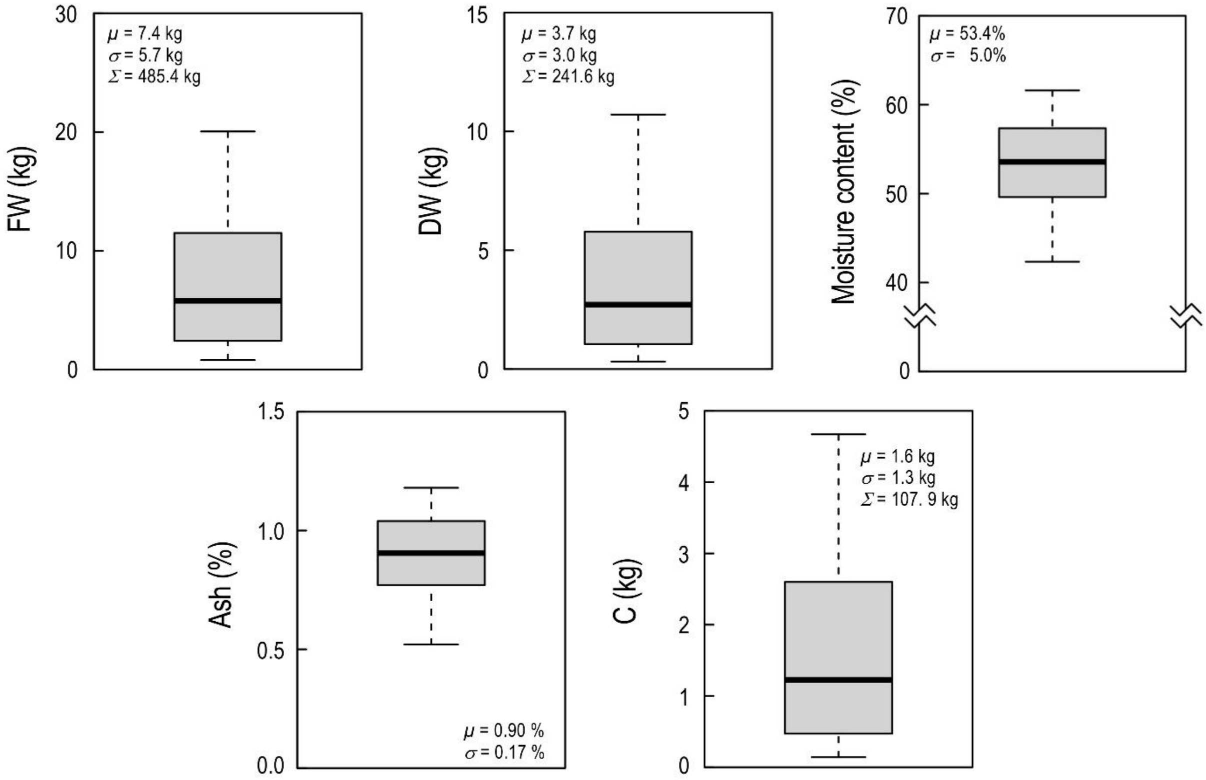

Fig. 4. Boxplots of fuelwood properties estimated by regression formulae as a function of stem diameter. Note: Number of estimated trees = 66. FW, fresh weight of above ground biomass except for leaves; DW, dry weight of above ground biomass except for leaves; C, carbon content of above ground biomass except for leaves; *μ*, mean; *σ*, standard deviation; ∑, total amount of estimated dry weight of wood in 66 trees. The whole tree values were estimated by regression formula listed in Table 2.

The high VMC value in fuelwood indicates that the biomass is flammable. In addition, the low AC also shows good characteristics of this biomass because the amount of residual combustion in the form of ash is small, so it is not necessary to clean the ignition furnace too often. Fuelwood with higher FCC has higher values of heat or higher energy production. In the present study, the mean VMC, AC, and FCC in total wood were 81.8%, 0.90%, and 17.3%, respectively (Table 1). These values in VMC and AC are in the same range as other wood species (Marsoem and Irawati 2016; Álvarez-Álvarez *et al*. 2018; Ruiz-Aquino *et al*. 2019; Irawati *et al*. 2020). However, the FCC of *I. tinctoria* in this study was relatively low. In contrast, the CV value of total wood in this study (16.4 kJ g^{-1}, Table 1) was in the range of other Indonesian hardwood species (Irawati *et al*. 2020) and meets European standards of solid biofuels (Kofman 2016).

High-density wood is suitable for energy material because it reduces the bulky characteristic of the biomass (San-Miguel *et al*. 2022) and higher energy per unit volume. The wood density of *I. tinctoria* tree biomass was measured under oven-dry conditions, and the average value was 0.686 g cm^{-3}. This value is lower than *Quercus cerris* L. (753 kg m^{-3} = 0.753 g cm^{-3}) but higher than *Quercus petraea* (Matt.) Liebl. (680 kg m^{-3} = 0.680 g cm^{-3}) and *Carpinus betulus* L. (678 kg m^{-3} = 0.678 g cm^{-3}) from Hungary (Pásztory *et al*. 2014). The results indicated that even in fast-growing trees, such as *I. tinctoria*, higher-density wood can be obtained.

The N content in the biomass occurs due to *I. tinctoria* belonging to Leguminosae. Leguminosae species can generally assimilate the N bacteria in their root to capture N from the atmosphere and store it in their biomass (Babalola *et al*. 2017). The absence of the S element in the biomass indicates that there are no hazardous elements that can cause producing toxic gas during combustion.

Based on values in VMC and AC, *I. tinctoria* tree biomass shows good characteristics as an energy raw material. However, the low FCC correlates with the low heating value and is unfavorable. The low CV is thought to be because of the young age of the *I. tinctoria* tree, so the lignin content in the plants is still low (Wadenbäck *et al*. 2004; Rencoret *et al*. 2011). Lignin has a high calorific value due to its high fixed carbon content. Although the total C content in *I. tinctoria* tree biomass reached 44.5%, the FCC was only 17.3%. It is suspected that the C contained in the *I. tinctoria* tree biomass is in extractives and hemicellulose forms, which are generally released in the form of volatile matter. Unfortunately, the authors did not analyze the chemical content of wood in this study.

According to data of dry weight per ha and CV, it can be estimated that in 1 ha of *I. tinctoria* stands with a spacing of 3 × 1 m^2 at 20 months of age, energy can be obtained as much as 46,400 kcal or equal to 53.9 kWh. Previous studies have shown that a 10 MW biomass power plant would require approximately 60,000 tonnes of biomass feedstock per year with an estimation of CV 19.8 MJ kg^{-1}, which can be supplied by forest residue from logging in Fiji (Prasad and Raturi 2021). Along with the characteristics of low AC and high WD_{OD}, *I. tinctoria* tree biomass is quite efficient to use as an energy raw material.

Effect of radial growth rate on fuelwood properties

The variance component ratio of the growth category in MC (83.7%) and AC (87.0%) showed relatively higher values (Table 3), suggesting that stem diameter class largely affected these properties. Based on the results of estimated random effect parameters, fuelwood properties of dominant trees can be characterized as follows: lower MC and AC, due to the lower drying energy and cleaner combustion. In addition, AC in twigs showed higher values compared to stems and branches (Table 1). This is because bark generally has a higher AC than xylem (Nosek *et al*. 2016), and the ratio of bark to xylem volumes is higher in twigs or branches than in stems. This result is similar with the previous study that the bark percentage of *Populus deltoides* ranged from 21.8% to 24.4% in small-sized diameters to 8.1% to 9.3% in large-sized diameters (Eslamdoust 2022). In addition, the effects of radial growth rate on WD_{OD} in this species might be minimal because the variance component ratio of the radial growth category showed less than 5%. This result suggests that dominant trees in this species do not always produce wood with a lower wood density, which usually leads to deterioration of fuelwood quality. Based on the results of this study, it is concluded that, in *I. tinctoria*, the difference in the size of the stem diameter affects the quality of the energy produced. However, larger-diameter trees can produce good fuelwood with lower AC. Thus, growth promotion by intensive silvicultural treatment might increase the yield of high-quality fuelwood. In addition, the promotion of tree breeding programs for increasing the wood yield might not decrease the fuelwood quality of this species.

CONCLUSIONS

In this study, the above-ground biomass and fuelwood properties were determined for *Indigofera tinctoria* L. planted at a space of 3 × 1 m^2 without any silvicultural treatments.

1. It was concluded that *I. tinctoria* is suitable as a plantation fast-growing tree species for an energy feedstock, although the yield of biomass should be increased. The potential of the produced biomass in this species was 7.4 tons ha^{-1} year $^{-1}$, suggesting that intensive silvicultural management, such as optimal planting spacing, and tree breeding programs are needed for increasing both yield and quality of biomass as the fuel.
2. Based on the results of estimated random effect parameters, fuelwood properties of dominant trees can be characterized as lower moisture content (MC) and ash content (AC). However, the different diameters did not affect the oven-dried wood density (WD_{OD}), meaning that a larger stem diameter tree still has high wood density. Biomass from this species would become favorable fuelwood in the local community
3. *Indigofera tinctoria* is a species that adapts to marginal land and can naturally regrow after harvest, making it profitable to reduce the planting costs.

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SUPPLEMENTARY MATERIAL

Table S1. Parameter in Regression Models

Property	Formula	Parameter													
		A					*b*					*c*			
		Estimates	SE	*t*-value	*p*-value		Estimates	SE	*t*-value	*p*-value		Estimates	SE	*t*-value	*p*-value
FW	Linear	3.2249	0.2352	13.712	<0.001		-7.8788	1.1768	-6.695	<0.001					
	Exp	0.58868	0.10583	5.562	0.001		0.47471	0.02458	17.214	<0.001					
	Logistic	22.5752	3.7701	5.988	0.001		118.9042	34.0442	3.493	0.013		0.79559	0.1069	7.443	<0.001
DW	Linear	1.7098	0.1372	12.463	<0.001		-4.4222	0.6864	-6.442	<0.001					
	Exp	0.22618	0.03823	5.917	0.001		0.51833	0.02574	20.139	<0.001					
	Logistic	12.10698	1.77221	6.832	<0.001		169.83683	40.23221	4.221	0.006		0.83370	0.08897	9.389	<0.001
MC	Linear	-2.854	0.490	-5.828	0.001		66.887	2.450	27.297	<0.001					
	Exp	68.594	2.960	23.173	<0.001		-0.054	0.009	-5.885	0.001					
	Logistic	27.612	71.897	0.384	0.714		-0.627	0.879	-0.714	0.502		0.058	0.314	0.185	0.860
VM	Linear	-0.09231	0.04847	-1.904	0.099		82.19218	0.24254	338.882	<0.001					
	Exp	82.193	0.244	337.498	<0.001		-0.001	0.001	-1.905	0.098					
	Logistic	81.516	0.535	152.275	<0.001		-0.018	0.038	-0.481	0.647		0.439	1.1359	0.386	0.713
Ash	Linear	-0.098	0.016	-6.071	0.001		1.362	0.081	16.870	<0.001					
	Exp	1.502	0.116	12.964	<0.001		-0.112	0.017	-6.416	<0.001					
	Logistic														
FC	Linear	0.190	0.058	3.310	0.013		16.4455	0.2877	57.16	<0.001					
	Exp	16.469	0.277	59.466	<0.001		0.010934	0.003323	3.291	0.013					
	Logistic	17.874	0.707	25.279	<0.001		0.1748	0.1817	0.962	0.373		0.4142	0.6106	0.678	0.523
WD$_{OD}$	Linear	0.014521	0.008906	1.63	0.147		0.617714	0.044563	13.86	<0.001					
	Exp	0.61993	0.04107	15.095	<0.001		0.02140	0.01295	1.652	0.142					
	Logistic														
CV	Linear	-0.09940	0.09774	-1.017	0.343		16.86027	0.48904	34.477	<0.001					
	Exp	16.865602	0.500241	33.715	<0.001		-0.006057	0.005966	-1.015	0.344		0.4142	0.6106	0.678	0.523
	Logistic	1.651e01	2.084e-01	79.258	<0.001		5.092e-17	4.602e-15	0.011	0.992		-4.962	1.318e01	-0.346	0.720

Note: SE, standard error; Exp, exponential; FW, fresh weight of above ground biomass except for leaves; DW, dry weight of above ground biomass except for leaves; MC, moisture content; VM, Volatile mater; FC, fixed carbon; WD$_{OD}$, fuelwood density including wood and bark at oven-dry condition; CV, calorific value.

Table S1. Continued

Property	Formula	Parameter													
		A					*b*					*c*			
		Estimates	SE	*t*-value	*p*-value		Estimates	SE	*t*-value	*p*-value		Estimates	SE	*t*-value	*p*-value
CC	Linear	0.76464	0.05947	12.858	<0.001		-1.9774	0.29754	-6.646	<0.001					
	Exp	0.10286	0.01832	5.613	0.001		0.51566	0.02714	19.000	<0.001					
	Logistic	5.1947	0.7027	7.392	<0.001		175.2857	46.0408	3.807	0.009		0.8546	0.0923	9.259	<0.001

Note: SE, standard error; Exp, exponential; CC, carbon contents of above ground biomass except for leaves

Table S2. Mean Absolute Error (MAE) in Each Regression Formula

Property	MAE		
	Linear	Exponential	Logistic
FW	0.918	0.506	**0.274**
DW	0.550	0.217	**0.099**
MC	**1.969**	1.932	53.422
VM			
Ash	**0.053**	0.052	0.900
FC	**0.220**	0.224	17.343
WD$_{OD}$			
CV			
CC	0.239	0.102	**0.047**

Note: FW, fresh weight of above ground biomass except for leaves; DW, dry weight of above ground biomass except for leaves; MC, moisture content; VM, Volatile mater; C, fixed carbon; WD$_{OD}$, fuelwood density including wood and bark at oven-dry condition; CV, calorific value; CC, carbon contents of above ground biomass except for leave. Values with bold style indicate selected formula (minimum MAE among three formulae or if the values were similar, the simpler formula was selected) in each property. Bars indicate that significant ($p < 0.05$) parameter estimates were not obtained in the formula.