Prediction of Density in Standing Trees of Various Wood Species in Natural Forests Using Near-infrared Spectroscopy

Imran Arra'd Sofianto[1]*, Ratih Damayanti[1], Djarwanto[1], Raden Gunawan Hadi Rahmanto[1], Dyah Ayu Agustiningrum[1], Rohmah Pari[1], Listya Mustika Dewi[1], Danang Sudarwoko Adi[1], Yuniawati, Sarah Andini[1], Mutia Herni Ningrum[1], Nur Safitri[1,5], Annisa Nur Fitriani[2], Warsito Purwo Taruno[2], Syamsul Budiman[3], Adhi Suprabana[3], Setiowati[3], and Sri Nugroho Marsoem[4]

Abstract

The density of wood is a crucial factor in determining its use as a construction material. The utilisation of near-infrared spectroscopy as a non-destructive testing (NDT) method has shown great potential in recent years. The estimation of wood density for a diverse range of trees and species seen in natural forest should be examined using NDT. The integration of density data and near-infrared spectroscopy allows for the development of a predictive model. This study utilised increment core sampling to examine density prediction using the near-infrared spectroscopy technique. The chemometrics increment core samples from several wood species were analized using cross-validation partial least squares regression (CV-PLSR) in order to construct a prediction density model. The research yielded a coefficient of determination for cross-validation (R^2CV) of 0.76 using 10 latent variables (LV) derived from the 1st derivative of 13 smoothing-point spectra within the wavelength range of 1200 – 1800 nm. This model was shown to be the most accurate for prediction. The outcome appeared satisfactory considering the quantity of LV for this small-scale sampling of increment cores obtained from various wood species. This study has demonstrated the feasibility of constructing a predictive model for multiple wood species.

Keywords: density, near-infrared spectroscopy, increment cores, thin wood, sampling, natural forest

Introduction

The natural forest of Kalimantan is abundant with numerous commercially valuable timber species, alongside a presence of endangered species. Accurate data regarding the density of various species grown naturally in forests is essential in determining whether or not to proceed with logging activities. The industry must comprehend the lawful species that can be harvested and their specific utility in construction. Endangered species are protected from industrial logging in natural forests due to their limited population size. These species have a limited capacity to selectively remove vegetation in modest quantitied for human use within the forest. Accurate data on density and species identification are crucial for effective forest management in the business.

In the last twenty years, numerous scientists have utilized near-infrared spectroscopy (NIRS) to predict the physical, chemical, and mechanical characteristics of wood products. Some notable studies include Via *et al*. (2003); Kelley *et al*. (2004); Schimleck (2007); Jiang *et al*. (2007); Inagaki *et al*. (2018); Mancini *et al*. (2019); Loureiro *et al*. (2022). Tsuchikawa and Kobori (2015) defined NIRS as a spectroscopic technique that utilises electromagneticradiation within the wavelength range of 750 to 2500 nm, commonly referred to as near-infrared. The NIR wave can be used to measure organic compounds that include X-H bonding, such as CH, OH, and NH (Manley 2014). Wood primarily comprises carbon, hydrogen, and oxygen, rendering it one of the quantifiable organic substances detectable by NIR technology. The utilisation of NIRS in the field of wood products shows great potential, as this technique is a form of non-destructive testing and evaluation (NDTE).

Sampling in natural forests for logging inventory has been conducted by utilising increment cores and thin wood sampling techniques to sample numerous species. Cores samples were collected using an increment borer at the diameter at breast height (dbh) of the stem. At the same time, thin wood samples were obtained by taking 1 cm thin of wood near the bark in size of 4 × 4 cm. These sampling procedures are the most straightforward way to acquire wood samples from standing trees and involve non-destructive sampling. According to Williams *et al*. (2015), tropical trees pose a challenge due to their chemical composition and mineral content, which renders them very resistant to bio-degradation. These mechanisms result in the durability of certain tropical trees. Thus, research employed thin wood sampling for complicated species, such as ulin (*Eusideroxylon zwageri*) and pelawan (*Tristaniopsis whiteana*).

This study utilised various wood species as samples to predict density using NIRS. In recent years, research in the field of NIRS for wood materials has indicated that density prediction in chemometrics typically focuses on a single wood species (Arriel *et al*. 2019; Zhang *et al*. 2022; Li *et al*. 2022). Nevertheless, this study aimed to utilise several wood species in order to predict fundamental wood density using the application of NIRS, a technique previously employed by Li *et al*. (2021). The key focus of this research is to utilize NIRS to accurately predict wood density by applying several wood species.

Utilising both increment cores and thin wood sampling, along with the measurement of their near-infrared spectra, is a highly effective approach for doing prediction analysis on the air-dry density. Multivariate analysis of cross-validation partial least squares regression (CV-PLSR) is performed to construct the density prediction. Increment cores and thin wood samples from multiple species in nature would be used as sampling methods for constructing this density prediction model. Utilising multiple species samples is intended to expand the range of values in density data, leading to improved accuracy in predictions.

Materials and Methods

Materials

Wood samples used in this research were taken from standing trees of natural forest with forest management rights by Trisetia Citra Graha, Co. Ltd. (PT TCG) located in Muara Singan, Gunung Bintang Awai, Barito Selatan, Central Kalimantan Province, Indonesia. There were 21 standing trees in the forest used for sampling. Two types of wood samples were collected: increment cores and thin wood. Increment cores samples consisted of 7 species, which were bangkirai (*Hopea sangal* Korth.), keruing (*Dipterocarpus acutangulus* Vesque), meranti merah getah putih (*Shorea rogusa* F. Heim), tengkawang (*Shorea stenoptera* Burck), terontong (*Microcos opaca* (Korth.) Burret), sintuk (*Cotylelobium* sp.), and benuang laring (*Syzigium* sp.). Thin wood samples consisted of all increment core samples' species plus seven species of ulin (*Eusideroxylon zwageri* Teijsm. & Binn.), simpur (*Dillenia reticulata* King), wayan (*Elateriospermum tapos* Blume), mengosi (*Santiria graffithii* Hook.f. Engl.), tarap (*Artocarpus odoritissimus* Blanco), merijang (*Sindora coriacea* (Baker) Prain), and pelawan (*Tristaniopsis whiteana* (Griff.) Peter G. Wilson & J.T. Waterh). Those seven species taken for thin wood samples were the trees that are hard to drill because of their hardness.

Sampling

Total number of samples for increment cores and thin wood samples were 281 and 61, respectively. The cores were acquired by the process of drilling using increment borers manufactured by Haglöf Sweden AB (Langsle, Sweden). The cores had a diameter of 0.5 cm and a cutting length of 2 cm. Thin wood samples of of 4 × 4 × 1 cm^3 were acquired using a hammer and wood chisel. Both samples were collected at the diameter at breast height (dbh). Core samples were collected from 7 species, while thin wood samples were collected from 14 species. The air-dry density (g cm^{-3}) of both samples was assessed. The air-dry density data were obtained by dividing the weight of the sample (g) at air-dry moisture content (MC) by the volume (cm^3) of the sample at air-dry MC. The volume was determined by submerging the sample in water at baker glass (where 1 g is equivalent to 1 cm^3). Subsequently, the air-dry samples were exposed to illumination, and their corresponding near-infrared spectra were measured across the entire wavelength range of 750 – 2500 nm. Figure 1 shows increment cores and thin wood samples utilised in this research.

NIR Spectra Acquisition

The near-infrared spectra of increment cores and thin wood samples were initially acquired under air-dry conditions (12% MC) prior to measuring the sample weight using a digital scale. The research utilised a Spectrum 100N FTNIR Spectrometer (PerkinElmer Inc., Waltham, Massachusetts, USA) located in the Integrated Laboratory of Bioproducts (iLaB), Research Center for Biomass and Bioproducts BRIN in Cibinong, Bogor, Indonesia as shown in Figure 2. The NIR lights illuminated the sample from below in mixed both of radial and transversal surface for increment cores samples and in tangential surface for thin wood samples. Increment cores samples have both transversal and radial mixed surfaces as the samples in tube shape taken upright from stem of standing tree. NIR spectra of both samples were acquired from 750 to 2500 nm with scan resolution of 16 cm^{-1} and accumulations of 32 scans. The result of NIR spectra measurements is absorbance values in according to its NIR wavelength.

Statistical Analysis

The density data (served as y) and their related near-infrared spectra data (served as x) were analyzed using multivariate analysis of leave-one-out cross-validation partial least squares regression (LOO CV-PLSR) to construct the density prediction model. All the spectra were pre-treated with a mean center before the analysis was performed. Wavelengths used for analysis were 750 – 2500 nm and 1200 – 1800 nm. Pre-treatments for spectra namelystandard normal variate (SNV), multiplicative scatter correction (MSC), and 1st derivative with 13 smoothing-point (sp) were applied. The best prediction result was decided by the highest value of the cross-validated coefficient of determination (R^2CV), the lowest number of latent variables (LV), and the lowest value of root mean square error of cross-validation (RMSECV), respectively.

Figure 1. Increment cores and thin wood samples.

Figure 2. Spectrum 100N FTNIR spectrometer.

Results and Discussion

Table 1 shows the samples' mean density (g cm^{-3}), including their local name and binomial nomenclature. The range of mean air-dry density of increment cores samples were 0.32 to 0.74, which were terontong to keruing.

The range of mean air-dry density for thin wood samples were 0.38 to 0.95 represented by terontong and benuang laring to pelawan. The comparison showed that the mean air-dry density data of thin wood samples is higher than that of increment cores samples, although with the same species or overall. Thin wood samples showing higher density are supposed to be thin wood samples located nearest the bark of the stem, which is mature wood (according to Bendtsen 1978 in Jones and Shmulsky, 2019). Number 8 to 14 of thin wood samples are the trees that could not be drilled because of their hardness, including ulin as shown in Figure 3. Figure 4 shows the histogram data for the samples. The standard deviation (std) of increment cores and thin wood samples are 0.1404 g cm^{-3} and 0.1919 g cm^{-3}, respectively.

Figure 5 shows the mean original NIR spectra with a 750 – 2500 nm wavelength from increment cores and thin wood samples. Redline spectra belong to increment core samples; the blue line spectra are for thin wood samples. Spectra of increment cores have higher absorbance than thin wood spectra. The surface of NIR spectra could acquire this; increment core samples have mixed radial and transversal surfaces, and thin wood samples have tangential surfaces. The tangential surface on wood has a lower absorbance of NIR spectra than measured on a transverse surface, as stated by Schimleck *et al*. (2007) in Fujimoto *et al*. (2008).

The result of CV-PLSR analysis is shown in Table 2 for different spectra applied. The best prediction model was obtained from the 1st derivative spectra with 13 smoothing-point (sp) and 1200 – 1800 nm wavelengths. These spectra result in R^2CV of 0.76 and RMSCEV of 0.0679 g cm^{-3} for increment core samples. This mean spectrum is shown in Figure 6. RMSECV value obtained from the best model (0.0679 g cm^{-3}) is under 0.1 g cm^{-3}. A scatter plot of the measured and predicted of density is shown in Figure 7. This value proved better prediction accuracy than the RMSECV value from thin wood samples (0.130 g cm^{-3}), higher than 0.1 g cm^{-3}. Wavelengths of 1200 – 1800 nm, free from noise, were included in the 1002 – 2130 nm wavelength range, as stated by Ma et al. (2019). R^2CV value of 0.76 is higher than result from 1st derivative spectra for density prediction analysis by Li *et al*. (2021) using 90° and mixed angles (R^2CV value: 0.63 and 0.59).

Table 1. Mean density of increment cores samples (a) and thin wood samples (b)

a) Increment cores samples

No.	Local names	Binomial nomenclature	Mean air-dry density ($g\ cm^{-3}$)
1.	Bangkirai	*Hopea sangal* Korth.	0.42
2.	Keruing	*Dipterocarpus acutangulus* Vesque	0.74
3.	Meranti merah getah putih	*Shorea rugosa* F.Heim	0.68
4.	Tengkawang	*Shorea stenoptera* Burck	0.33
5.	Terontong	*Microcos opaca* (Kurth.) Burret	0.32
6.	Sintuk	*Cotylelobium* sp.	0.58
7.	Benuang laring	*Syzygium* sp.	0.37

b) Thin wood samples

No.	Local name	Binomial nomenclature	Mean air-dry density ($g\ cm^{-3}$)
1.	Bangkirai	*Hopea sangal* Korth.	0.56
2.	Keruing	*Dipterocarpus acutangulus* Vesque	0.79
3.	Meranti merah getah putih	*Shorea rugosa* F.Heim	0.72
4.	Tengkawang	*Shorea stenoptera* Burck	0.40
5.	Terontong	*Microcos opaca* (Kurth.) Burret	0.38
6.	Sintuk	*Cotylelobium* sp.	0.56
7.	Benuang laring	*Syzygium* sp.	0.38
8.	Merijang	*Sindora coriacea* (Baker) Prain	0.67
9.	Simpur	*Dillenia reticulata* (King)	0.74
10.	Wayan	*Elateriospermum tapos* Blume	0.87
11.	Ulin	*Eusideroxylon zwageri* Teijsm. & Binn.	0.85
12.	Pelawan	*Tristaniopsis whiteana* (Griff.) Peter G.Wilson & J.T.Waterh.	0.95
13.	Mengosi	*Santiria griffithii* (Hook.f.) Engl.	0.87
14.	Tarap	*Artocarpus* sp.	0.82

Figure 3. Stem of ulin (*Eusideroxylon zwageri* Teijsm. & Binn.).

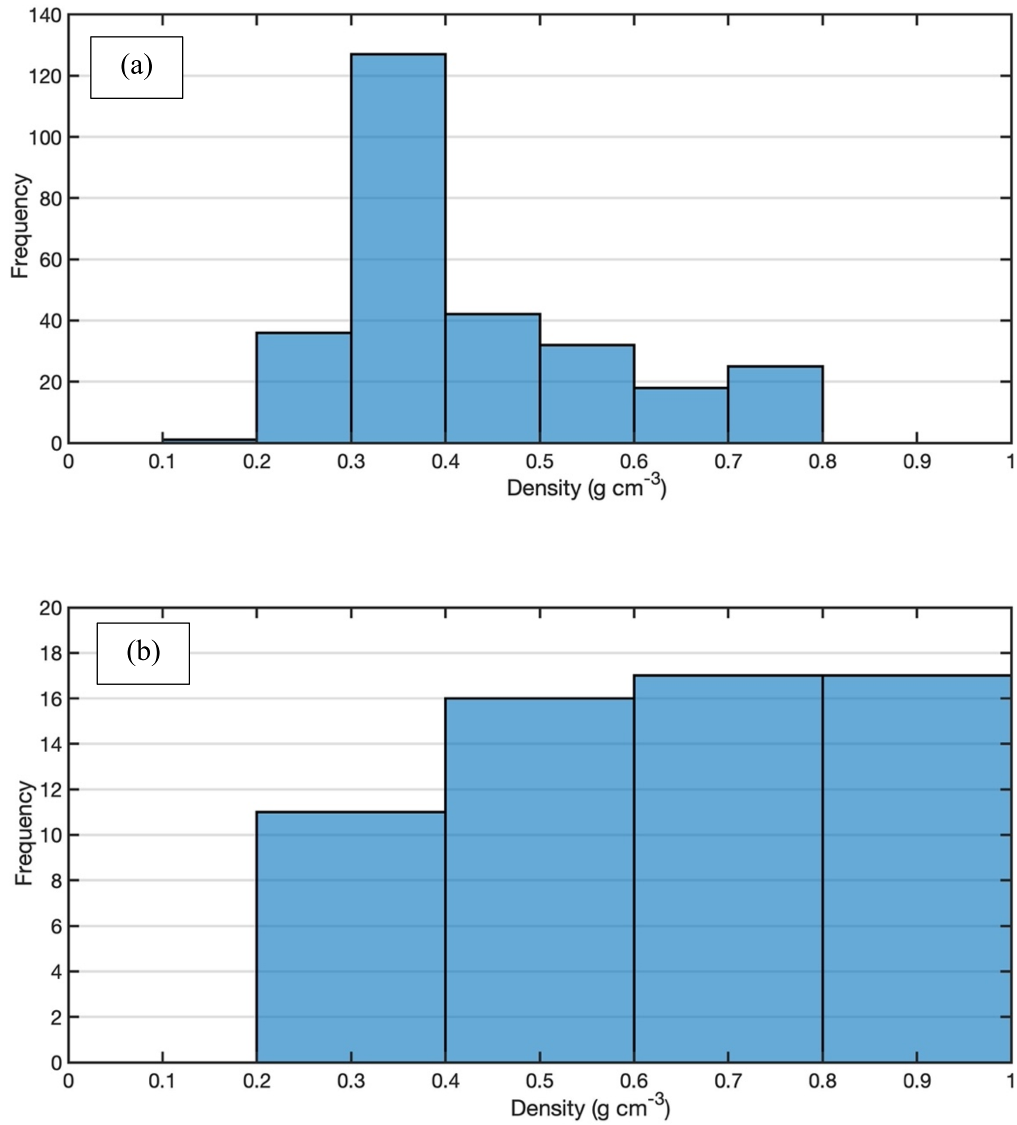

Figure 4. Histogram of increment cores density with *n* = 281 (a) and thin wood samples density with *n* = 61 (b).

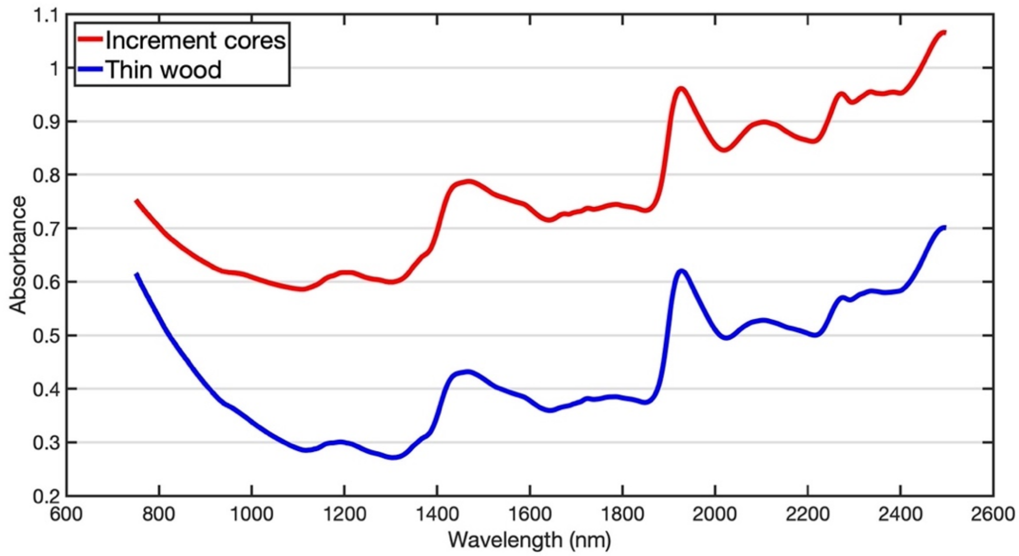

Figure 5. The mean original NIR spectra of increment cores and thin wood samples for wavelength 750 to 2500 nm.

Table 2. Comparison of spectra analysis on the prediction model using CV-PLSR

a) Increment cores samples*

Spectra	Wavelength	LV	R^2CV	RMSECV ($g\ cm^{-3}$)	RPD
Original	750 – 2500	20	0.7071	0.0731	1.9205
Original	1200 – 1800	17	0.7819	0.0634	2.2143
SNV	750 – 2500	19	0.7193	0.0717	1.9580
SNV	1200 – 1800	17	0.7862	0.0628	2.2355
MSC	750 – 2500	17	0.7184	0.0721	1.9472
MSC	1200 – 1800	16	0.7842	0.0632	2.2214
1^{st} der. 13 sp	750 – 2500	13	0.6253	0.0838	1.6753
1^{st} der. 13 sp	1200 – 1800	10	0.7564	0.0679	2.0676

*LV: latent variable; R^2CV: coefficient of determination for cross-validation; RMSECV: root mean square error of cross-validation; RPD: ratio of performance to determination (std y/RMSECV); SNV: standard normal variate; MSC: multiplicative scatter correction; der.: derivative; sp: smoothing-point

b) Thin wood samples

Spectra	Wavelength	LV	R^2CV	RMSECV ($g\ cm^{-3}$)	RPD
Original	750 – 2500	13	0.2348	0.1474	1.3021
Original	1200 – 1800	9	0.3261	0.1441	1.3319
SNV	750 – 2500	7	0.3499	0.1442	1.3310
SNV	1200 – 1800	14	0.0869	0.1593	1.2048
MSC	750 – 2500	7	0.3536	0.1438	1.3347
MSC	1200 – 1800	10	0.0328	0.1709	1.1230
1^{st} der. 13 sp	750 – 2500	4	0.4581	0.1354	1.4175
1^{st} der. 13 sp	1200 – 1800	9	0.4470	0.1305	1.4707

*LV: latent variable; R^2CV: coefficient of determination for cross-validation; RMSECV: root mean square error of cross-validation; RPD: ratio of performance to determination (std y/RMSECV); SNV: standard normal variate; MSC: multiplicative scatter correction; der.: derivative; sp: smoothing-point

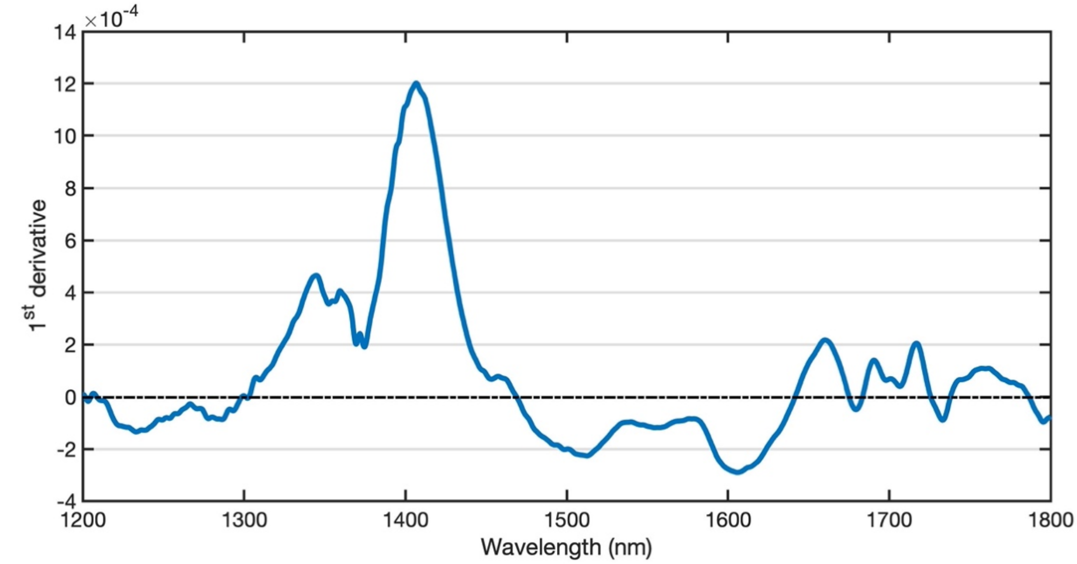

Figure 6. Mean spectra of the 1st derivative with 13 smoothing-point of increment cores samples in the wavelength range of 1200 – 1800 nm as the best spectra from analysis for increment core samples.

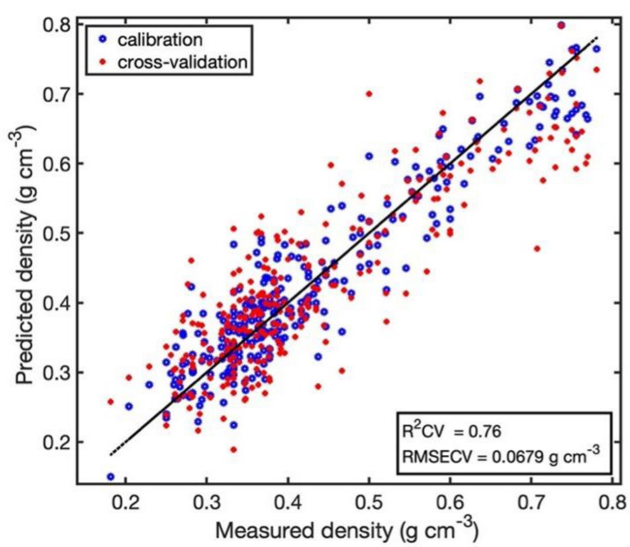

Figure 7. Scatter plot of the measured and predicted density of the 1st derivative with 13 smoothing-point in the wavelength range of 1200 – 1800 nm as the best spectra from increment core samples.

Conclusions

A successful density prediction model was developed combining near-infrared spectroscopy (NIRS) with increment cores and thin wood sampling for numerous species from natural forests. The research findings indicate that increment cores had a higher prediction accuracy compared to thin wood samples, with an R^2CV value of 0.76 than 0.45, respectively. The aforementioned outcome was derived from the 1st derivative spectra with 13 sp and a 1200 – 1800 nm wavelength. The RMSECV value of 0.0679 g cm^{-3} is considered modest, as it falls below the threshold of 0.1 g cm^{-3}, indicating outstanding performance. The implementation of wavelength cuts has greatly enhanced the predictive accuracy in comparison to using the whole near-infrared (NIR) wavelength range. This study also found that species with high density growing in natural forest were demanding to be drilled using increment borer hence a more appropriate method is required.

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Imran Arra'd Sofianto, Ratih Damayanti, Djarwanto, Raden Gunawan Hadi Rahmanto, Dyah Ayu Agustiningrum, Rohmah Pari, Listya Mustika Dewi, Danang Sudarwoko Adi, Yuniawati, Sarah Andini, Mutia Herni Ningrum
Research Center for Biomass and Bioproducts, National Research and Innovation Agency (BRIN)
Kawasan Sains dan Teknologi Dr. (HC) Ir. Soekarno, Jalan Raya Bogor KM.46, Cibinong, Bogor 16911
Tel. : +6282363243080
E-mail : imra003@brin.go.id

Nur Safitri
Department of Forest Products and Technology, Faculty of Forestry and Environment, IPB University
Jalan Ulin Kampus IPB, Dramaga, Bogor 16680

Annisa Nur Fitriani
Warsito Purwo Taruno
CTech Labs Edwar Technology
Jalan Jalur Sutra Kavling Spektra Blok 23 BC No. 10 – 12, Panunggangan, Pinang, Kota Tangerang

Syamsul Budiman
Adhi Suprabana
Setiowati
PT Wanantara Alesha Sadhana
Jalan Iskandar Muda 17, Jakarta

Sri Nugroho Marsoem
Department of Forest Products and Technology, Faculty of Forestry, Universitas Gadjah Mada
Jalan Agro No.1, Bulaksumur, Sleman 55281