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Surface Characteristics and Acoustical Properties of Bamboo Particle Board Coated with Polyurethane Varnish

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Abstract: Using bamboo particle board as a wall divider, a furniture component, or an automotive component with a sound absorber function may be a viable option for architects and engineers seeking to achieve desired acoustical qualities, including noise reduction. However, there is still a dearth of research on the effect of particle board finishing and coatings on acoustical sound absorption and noise reduction qualities. This study, therefore, aims to determine the surface characteristics and acoustical properties of bamboo particle board, coated with polyurethane (PU). The single-layer homogeneous particle boards were constructed using particles classified as fine and coarse with two different board densities, and coated with a high-quality PU lacquer. This study found that the coating treatment of 0.3 mm 0.6 mm succeeded to significantly decrease surface roughness, as well as thickness, swelling, and water absorption, with the thickness coating as a dominant factor compared with board density and board particle size. Adding a PU coating increases sound absorption performance at low frequencies, but significantly reduces acoustical properties at high frequencies. The increase of particle board density leads to the decrease in noise reduction coefficient capability. Results obtained from this study are useful to determine the optimal coating thickness in terms of evaluating acoustical panel products.

Keywords: coating thickness; surface roughness; sound absorption; noise reduction; bamboo particle board

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Citation: Karlinasari, L.; Adzkia, U.; Sudarsono, A.S.; Larasatie, P.; Amin, Y.; Nugroho, N. Surface Characteristics and Acoustical Properties of Bamboo Particle Board Coated with Polyurethane Varnish. *Forests* **2021**, *12*, 1285. https://doi.org/10.3390/f12091285

Academic Editors: Tripti Singh and Angela Lo Monaco

Received: 16 August 2021
Accepted: 15 September 2021
Published: 18 September 2021

1. Introduction

Sustainability concerns have moved the global economy towards using renewable materials for producing sustainable products. The trends have accelerated the growth of utilizing wood and bamboo for household and building products, including as construction materials for high-rise buildings [1,2]. In addition to their sustainability values, the public has praised the aesthetic appearance of wood and bamboo. Due to these natural characteristics, wood and bamboo have important roles for achieving sustainable development goals (SDGs), particularly goal no. 11 (sustainable cities and communities) and no. 12 (responsible consumption and production).

In Asia and some parts of South America, bamboo associates with their history and represents people's lifestyle [3]. Bamboo has long been commercialized, and its industry has become a global, multimillion-dollar business. However, the manufacturing may produce a large amount of waste, especially in the processing phase [4]. To answer the challenges, bamboo particle boards are produced, combining bamboo and its waste. The commercial products of bamboo particle boards are available in the market, such as in China, Malaysia, Costa Rica, and Vietnam [3].

Numerous studies were conducted on particle board made from various bamboo species. Karlinasari et al. [5] identified almost 220 publications using the keywords "particle board bamboo" in the Scopus and Science Direct online scientific search engines. Most of these studies examined bamboo particle board's physical, mechanical, and natural resistance [3,5–12]. Karlinasari et al. [5], Widyorini [6], and Shah et al. [13] are among the few researchers that have examined the surface characteristics of bamboo panel products. Combining the surface condition with finishing treatment can be a critical step in achieving a good-looking final product. Coating applications of varnishes, stains, and paints are the most popular method in order to enhance the stability and appearance of the wood and wood-based materials.

There is a correlation between the surface quality, the finishing treatment of the coating, the intended usage, and the aesthetic value of the product. According to Dilik et al. [14] and Darmawan et al. [15], coating application as a finishing treatment seeks to improve the aesthetic value of the product, conceals some of the product's flaws (i.e., texture), and extends the product's service life. The type of coating and the quality of the surface are two variables that can affect the product's quality [16]. The type of coating is critical for bonding, ultraviolet resistance, layer hardness, abrasion resistance, and layer thickness [15,17,18]. Cellulosic, polyurethane (PU), and water-based coating methods create a protective and aesthetic film on the surface of wood-based materials. PU is an environmentally friendly material containing significantly reduced volatile organic compounds and is largely found in coatings, adhesives, finishes, etc. PU applications, in particular, have a number of advantages, including flexibility, abrasion resistance, chemical and solvent resistance, good adhesion, rapid drying, resilience to weather conditions, and non-yellowing [19,20]. For these reasons, PU-coated surfaces perform superiorly to those coated with alternative materials. As a result, the furniture business makes extensive use of this application [21].

Nowadays, acoustical materials, both absorption and insulation, play a critical role in a wide variety of applications, for example, as wall partitions, building barriers, machine tool applications, vehicle components, and furniture components. Bio-composite materials are chosen due to their usage of natural fibers that are eco-friendly, lightweight, aesthetic, and also have a high modulus, low thermal expansion, and a high specific strength [22–25]. Some of these materials are commercially available, while the majority are still in the prototype stage [24]. Bamboo, kenaf, and coco fibers are excellent sound absorbers, while cork and recycled rubber layers provide adequate sound insulation. Karlinasari et al. [12] discovered that low-density bamboo particle board is effective in absorbing sound at both low and high frequencies. Woven bamboo [26], sandwich particle board with bamboo strands as the face sheet [27], and hollow-structured bamboo are all effective sound absorbers. Additionally, Koizumi et al. [28] and Karlinasari et al. [12] stated that the particle size of bamboo must be taken into account when determining the function of acoustic qualities, such as sound absorption or sound insulation.

The usage of particle board as a wall divider, a furniture component, or an automotive component [1] with a sound absorber function may be a viable option for architects and engineers seeking to achieve desired acoustical qualities, including noise reduction. There is still a dearth of research on the effect of particle board finishing and coatings on the acoustical sound absorption and noise reduction qualities. A PU coating on certain spruce wood species for piano soundboards resulted in an increase in sound absorption when compared to untreated spruce wood species. The sound absorption coefficients of the four covered spruce species improve as the coating thickness grows from 0.30 to 0.60 mm [29]. While the PU application greatly increases sound absorption between 1600 and 2000 Hz, the value of sound absorption is reduced to between 250 and 1500 Hz. The previous study concentrated on the coating effect on solid boards with a low absorption coefficient [29]. While the coatings' effect on boards with a high absorption coefficient, such as particle boards, has not been well investigated yet. Since it is beneficial to determine the influence of coating on the absorption performance of particle boards, this study aims to determine the surface characteristics and acoustical properties of bamboo particle board, coated with PU.

2. Materials and Methods

2.1. Materials

Due to its wide distribution in tropical areas and its huge dimensions, we chose *Betung* bamboo species (*Dendrocalamus asper*) to make the board samples. The single-layer homogeneous particle boards were constructed using particles, classified as fine and coarse. The dimensions of the coarse particles were (10.10 ± 1.101) mm in length, (2.14 ± 0.344) mm in width, and (0.50 ± 0.015) mm in thickness. Meanwhile, fine particles were manufactured to have a 10-mesh sieve. Medium density particle board with a density of 0.4 g/cm^3 and 0.6 g/cm^3 in a thickness of 1 cm was bonded using diphenylmethane diisocyanate resin (MDI resin). All the boards were air dried to a moisture content of around 9%. Two papers by Karlinasari et al. [5,12] outlined the technique for obtaining fine and coarse particles, as well as the manufacturing of particle board panels. Following that, the board samples were cut into circular discs with a diameter of 10 cm and 3 cm for acoustical characteristics testing.

The particle board's surface was coated with a high-quality PU lacquer, PUL-91 acrylic non-yellowing clear lacquer with thinner polyurethane MD (PT Propan Paint Specialist, Indonesia) was used for the topcoat at 40% of solid content. The PU coating utilized in this study was a mixture of the primary coating material, a clear gloss topcoat, and a ratio of 4:1:2 for primer: curing agent: thinner, as specified by the supplier. PU MD was utilized as the thinner. The mixture was mixed at a room temperature and had a shelf life of 6–8 h after mixing. This PU had a spread rate of 3.8 m^2/L set spray.

2.2. Methods

2.2.1. Coating Application

In this study, unsanded air-dried particle boards were used. On the particle board, an exterior layer of PU lacquer was applied. At certain sound frequencies, this coating is shown to considerably boost the sound absorption coefficient of Sitka and spruce wood [29,30]. The spraying coating method was applied to all samples (Figure 1). The application of PU-coating samples was established at thicknesses of 0.30 mm and 0.6 mm, as shown in Table 1. Coating was applied using a spray gun type F75 tube with a 400-cc capacity and a typical nozzle size of 1.5 mm to 2.0 mm. The spraying process used to obtain the desired thickness was described in Rasyid et al. [31]. The spraying distance was approximately 100 mm, the spray gun pressure was 0.0827 MPa, the residual tube pressure was 0.1378 MPa, and the target thickness was 0.1 mm. To produce a coating thickness of 0.3 mm, the coating was applied three times with an overnight curing interval time at 30 °C between each application. While to achieve a coating thickness of 0.6 mm, six spraying applications were made on the discs. All coated discs were then conditioned for about three days to ensure that they were totally dry prior to thickness measurement and testing. Three particle board discs were used as samples for each coating treatment. The board thickness before and after coating was then measured using a micrometer. The morphology of the samples was observed using scanning electron microscopy (SEM, JSM-IT200, InTouchScope™ SEM Series).

Figure 1. Application of spraying method for coating.

Table 1. Sample condition in experimental design.

Board Density (BD)	Particle Geometry	PU Coating Thickness	Code
BD 0.4 g/cm^3	Fine particles	un-coated (control)	F,d0.4,c0
		0.3 mm	F,d0.4,c0.3
		0.6 mm	F,d0.4,c0.6
	Coarse particles	un-coated (control)	C,d0.4,c0
		0.3 mm	C,d0.4,c0.3
		0.6 mm	C,d0.4,c0.6
BD 0.6 g/cm^3	Fine particles	un-coated (control)	F,d0.6,c0
		0.3 mm	F,d0.6,c0.3
		0.6 mm	F,d0.4,c0.6
	Coarse particles	un-coated (control)	C,d0.6,c0
		0.3 mm	C,d0.6,c0.3
		0.6 mm	C,d0.6,c0.6

2.2.2. Surface Quality

The surface roughness and wetting behavior of particle boards that were not sanded were examined to assess the surface quality. The surface roughness was determined with a diamond tip stylus in a radius of 5 μm using the roughness tester Mittoyo Surfest SJ 210 (Mitutoyo Corporation, Takatsutu City, Kanagawa, Japan). Each sample was read using two randomly chosen point measurements with a tracing length of 15 mm. The roughness of the surface was estimated using the mean deviation between valleys and peaks (Ra). The evaluation was then continued to determine wettability by measuring the contact angle (CA) between the water and the surface following the sessile drop, using the thorough approach described in Darmawan et al. [15]. CA values are critical for determining wettability in terms of hydrophilicity properties.

The thickness swelling and water absorption were measured to evaluate the ability of the product in absorbing water related to the hygroscopicity characteristics as well as dimensional stability of the product. Samples were immersed in the water at a temperature of 25 °C ± 2 °C for 24 h. After the soaking time, the samples were taken out from the water and the board surfaces were dried immediately using a clean dry cloth. The weight and thickness of the samples were measured and calculated based the sample condition before and after immersion.

2.2.3. Acoustical Properties of Sound Absorption and Noise Reduction Coefficient

Acoustic properties were determined based on sound absorption characteristics. The sound absorption was determined using the normal incidence concept as defined in ISO 10534-2 [32]. SW422 and SW477 impedance tubes from BSWA [33,34] were used for the measurement.

This impedance tube system, consisting of several instruments, such as measurement microphones, digital to analog converter, power amplifier, and metal tube, is shown in Figure 2a, while the impedance tube system consists of two sub systems as shown in Figure 2b. The first sub system was a white noise generator. The white noise was generated digitally from a laptop and was converted into analog signal by a digital-to-analog converter with a sampling rate of 48 kHz. The signal was amplified using a power amplifier and was sent to the speakers which generated inside the metal tube.

The second sub system was the measurement system which consisted of two measurement microphones, a digital-to-analog converter, and a laptop. The microphones converted the standing waves inside the tube into electric signal. The signal was converted into digital signal by the digital-to-analog converter with the sample rates of 48 kHz and sent into the laptop.

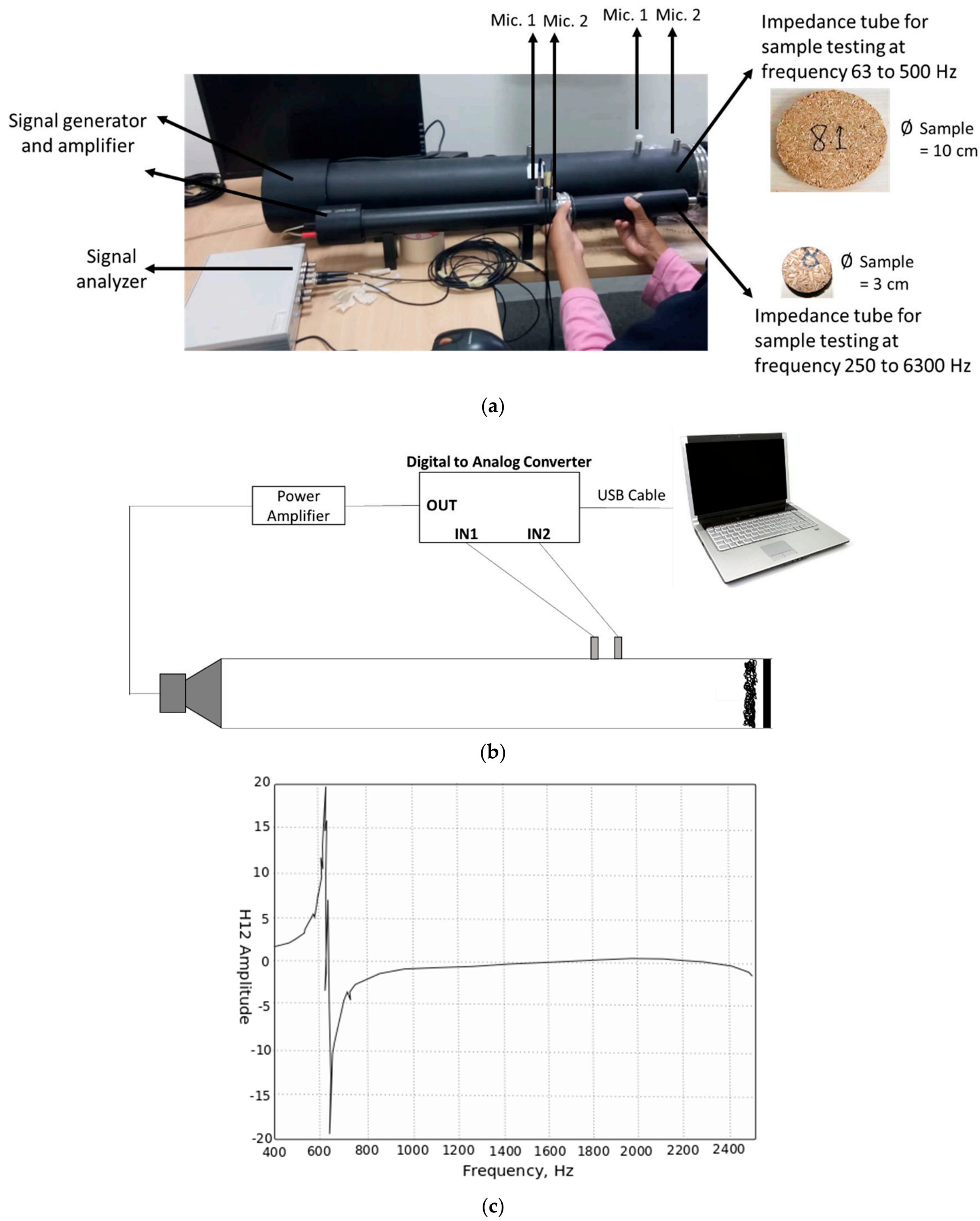

Figure 2. (**a**) Experimental testing of impedance tube for determination of sound absorption, (**b**) schematic of the impedance tube system, (**c**) transfer function signal from two microphones.

On a rigid end, the samples were placed. Standing waves were formed as a result of phase interference between the waves in the tube that were incident on and reflected from the test sample. The standing waves captured with the two microphones was calculated to get the transfer function signal as shown in Figure 2c. The transfer function was used to determine the sound absorption coefficient, α.

Three- and ten-centimeter-diameter samples were used. Two distinct samples with diameters of 10 cm were used to determine the sound absorption between 63 and 500 Hz, and two samples with a diameter of 3 cm were used to determine the sound absorption between 250 and 6300 Hz. The data were merged to provide the measurement result for the frequency range 63–6300 Hz displayed in 1/3 octave, for which the test instrument automatically calculated the sound absorption coefficient, α. The data was represented in this study over a frequency range of 200–5000 Hz to accommodate architectural applications. Additionally, this frequency range was chosen to approximate the generally used NRC value.

The coefficient of sound absorption of composite materials varies with frequency. The noise reduction coefficient (NRC) was determined using an average of four measurements at frequencies of 250, 500, 1000, and 2000 Hz [35,36].

2.2.4. Statistical Analysis

Multiple regression analysis with the backward method was used to determine the effect of board density, particle size, and PU-coating thickness on surface roughness and acoustics. The study was conducted using the SPSS Statistics 25 software (IBM, Armonk, NY, USA) with a confidence level of 95%.

3. Results and Discussion

3.1. Surface Quality

The PU coating was used on wood surfaces as a varnish application, for improving appearance, and as a protective layer, for improving the wood resistance to external environmental degradation factors. The evaluation of entering the coating on particle board is shown in Figure 3. It was calculated based on the thickness differences between and after coating. The spray application gave the resulting differences of about 12% and 6% from the target coating thickness of 0.3 mm and 0.6 mm, respectively. The coating filled the gap in the void between the particles in the board composite. The technique of spraying application affected the entering of PU lacquer. Aydin [37] and Gindl et al. [38] mentioned that this was related to interfering coating penetration or the anchoring ability of the coating to the wood substrate because of surface inactivation.

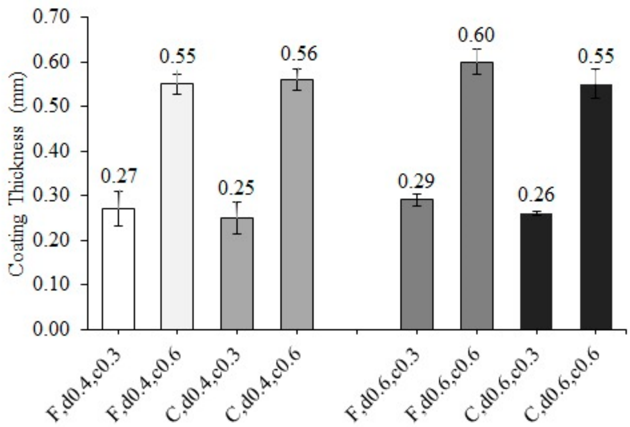

Figure 3. The final coating thickness of 0.3 mm and 0.6 mm at various particle geometry and board density of particle board.

In PU coating on experimental samples, the glossy, water-based, two-component wood varnishes produced with nanotechnology were used. Figure 4 shows the SEM images of uncoating and coating bamboo particle board including how the PU-coating adheres to the bamboo particles. This indicates that the PU coating had penetrated and covered the board surface. The higher the thickness coating, the smoother the surface. The smoothest surface was observed for composite board at a coating thickness of 0.6 mm. The images confirmed that the surface roughness decreased significantly, as shown in Figure 5. Analysis of variance revealed that coating thickness is a dominant factor on the surface roughness whereas other variables of board density and particle size might be negligible (Table 2). Nemli et al. [39] mentioned the raw material type, pressure, board density, and shelling ratio were variables affecting the surface quality of the particle board. Our study found that the highest surface roughness was obtained in uncoated samples. A significant decrease of up to 80% was observed on the PU coated surface. The average surface roughness values were 8.28 µm and 6.84 µm for the uncoated board density 0.4 g/cm^3 and 0.6 g/cm^3, respectively. A study by Widyorini [6] on bamboo particle board, using the same species bonded by sucrose, revealed the surface roughness of about 12 µm. Overall, the average surface roughness of 0.3 mm PU coating thickness bamboo particle board was 2.08 µm, whereas at 0.6 mm PU coating was 1.62 µm, as shown in Figure 5.

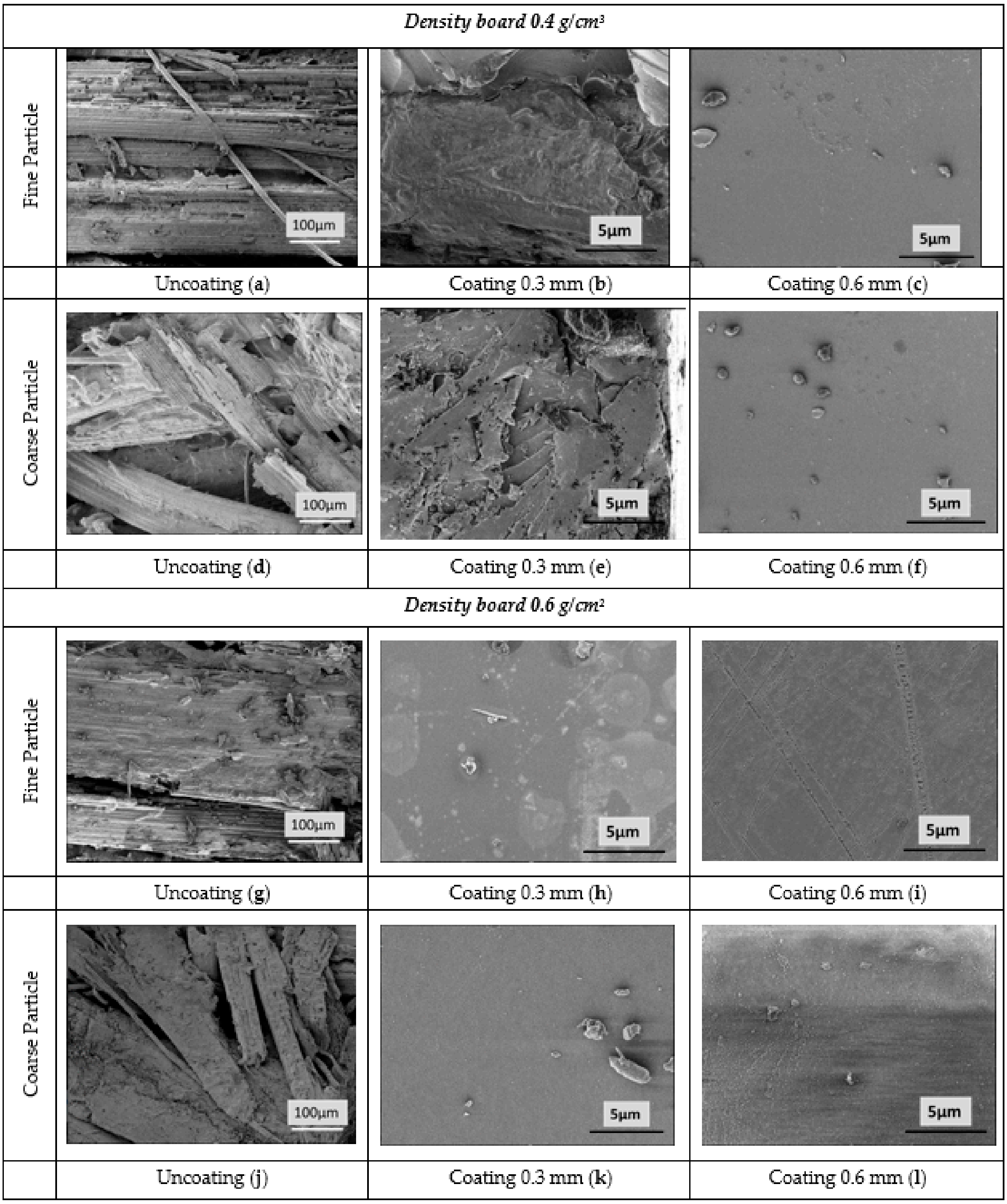

Figure 4. SEM images of uncoating (**a**,**d**,**g**,**j**) in 100× magnification; and coating treatment with 0.3 mm (**b**,**e**,**h**,**k**) and 0.6 mm (**c**,**f**,**i**,**l**) thickness coating at bamboo particle board (2000× magnification).

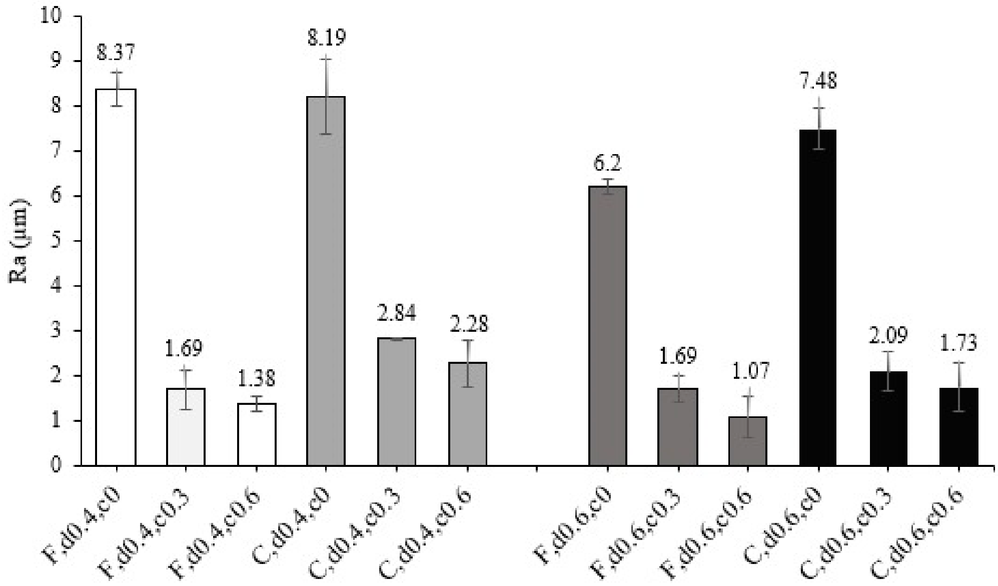

Figure 5. Surface roughness (Ra) values of bamboo particle board at various PU coating thickness with difference particle size and board density.

Table 2. Analysis of variance (ANOVA) of multiple regression for the effect of PU coating thickness, different particle size, and board density on the surface roughness (Ra) values.

	Model	df	Sum of Squares	Mean Square	F	Sig. ($p \leq 0.05$)
1	Regression	3	148.063	49.354	25.214	0.000 [a]
	Residual	20	39.149	1.957		
	Total	23	187.212			
2	Regression	2	144.688	72.344	35.726	0.000 [b]
	Residual	21	42.524	2.025		
	Total	23	187.212			
3	Regression	1	141.313	141.313	67.733	0.000 [c]
	Residual	22	45.899	2.086		
	Total	23	187.212			
		Coefficient	**Standard Error**	**t Stat**	***p*-Values**	
1	(Constant)	9.694	1.428	6.789	0.000	
	Board density	−0.750	0.571	−1.313	0.204	
	Particle size	0.750	0.571	1.313	0.204	
	Coating thickness	−2.972	0.350	−8.497	0.000	
2	(Constant)	10.819	1.162	9.311	0.000	
	Particle size	−0.750	0.581	−1.291	0.211	
	Coating thickness	−2.972	0.356	−8.354	0.000	
3	(Constant)	9.694	0.780	12.427	0.000	
	Coating thickness	−2.972	0.361	−8.230	0.000	

Notes: [a] Predictors: (constant), board density, particle size, PU coating thickness; [b] Predictors: (constant), particle size, PU coating thickness; [c] Predictors: (constant), PU coating thickness.

Surface roughness is related to contact angle in terms of wetting behavior. The rougher surface generated lower contact angle (CA) and ensured better wettability [15]. In terms of comparison between particle sizes, the result found the coarser of the surface roughness (Figure 5), the lower of the CA (Figure 6), which means better hydrophilicity. Wettability is an important parameter to support information on interactions between wood surface and liquids including in wood finishing treatment. Higher wettability provides better bonding quality of varnish [15].

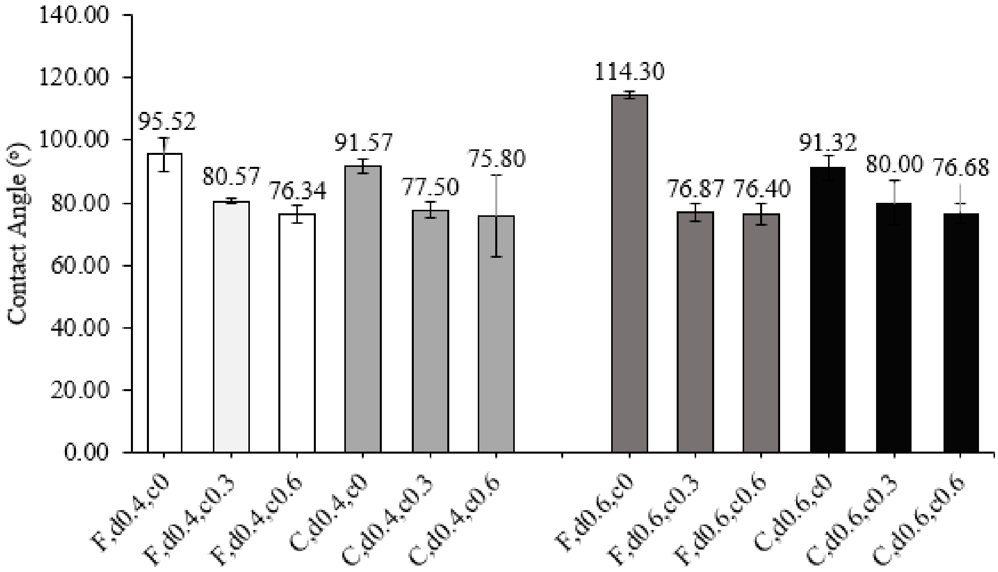

Figure 6. Contact angle (CA) values of bamboo particle board at various PU coating thickness with difference particle size and board density at 0 s.

Our study found that the thickness coating was significantly influenced as a dominant factor on the decreasing of CA. This is revealed by ANOVA (Table 3). In general, uncoated particle board had a contact angle more than 90° at 0 s wetting process, while the coated board possessed in the range of 76° to 81°. Other board types of laminated bamboo revealed the CA value about 70° at 0 s wetting process [13]. The higher thickness PU coating led to decreased contact angle. It was explained that a PU-coating lacquer of 0.6 mm thickness spread better to the surface material than 0.3 mm, although the differences were only in the range of 1% to 5% for both.

Table 3. Analysis of variance (ANOVA) of multiple regression for the effect of PU coating thickness, different particle size, and board density on the contact angle (CA) values.

	Model	df	Sum of Squares	Mean Square	F	Sig. ($p \leq 0.05$)
1	Regression	3	2091.965	697.322	11.106	0.000 [a]
	Residual	20	1255.784	62.789		
	Total	23	3347.749			
2	Regression	2	2036.376	1018.188	16.305	0.000 [b]
	Residual	21	1311.373	62.446		
	Total	23	3347.749			
3	Regression	1	1913.866	1913.866	29.364	0.000 [c]
	Residual	22	1433.884	65.177		
	Total	23	3347.749			
		Coefficient	**Standard Error**	**t Stat**	***p*-Values**	
1	(Constant)	108.492	8.087	13.415	0.000	
	Board density	3.044	3.235	0.941	0.358	
	Particle size	−4.519	3.235	−1.397	0.178	
	Coating thickness	−10.937	1.981	−5.521	0.000	
2	(Constant)	113.058	6.452	17.522	0.000	
	Particle size	−4.519	3.226	−1.401	0.176	
	Coating thickness	−10.937	1.976	−5.536	0.000	
3	(Constant)	106.280	4.360	24.376	0.000	
	Coating thickness	−10.937	2.018	−5.419	0.000	

Notes: [a] Predictors: (constant), board density, particle size, PU coating thickness; [b] Predictors: (constant), particle size, PU coating thickness; [c] Predictors: (constant), PU coating thickness.

The lower CA values refer to the easiness of a liquid to enter and/or spread to the surface material. In addition to the decorative and excellent surface, the purposes of particle board coating are to suppress the absorption of water and humidity, in terms of dimensional stability, to extent its service life [14,39]. For this reason, it is important to determine the physical properties of thickness swelling (TS) and water absorption (WA) after coating treatment. TS and WA are measurable criterions for structural wood panel performance, and it can occur when a particle board is exposed to free (liquid) water and capillary action which gradually increases the moisture content. An observable swelling occurs along the face of the particle board as an abrupt bump along the exposed edge [40]. Furthermore, there are some factors that influence thickness swelling in particle board, such as product thickness, binding adhesive, presence and type of a coating, surfactants, and particle board density.

The results, as shown in Figures 7 and 8, found that the coating treatment succeeded to decrease the TS and WA by about 40 to 50% from uncoated to 0.3 mm and 0.6 mm thickness coating, respectively. An exception was coarse particle board from uncoated to board at 0.3 mm coating thickness for TS, and at the board density 0.6 g/cm^3 for both fine and coarse particle board from uncoated to board at 0.3 mm coating thickness for WA, which was about 10 to 25%. ANOVA revealed that the dominant factor on thickness swelling was thickness coating (Table 4), while the dominant factors of water absorption were particle size and coating thickness (Table 5). This related to the effectiveness of compounds to deeply penetrate the composite bamboo, as shown in Figures 7 and 8. Mantanis and Papadopoulos [41] mentioned that the nanotechnology compounds provide a high protection moisture content. The particle board coated by a commercial coating in a water-based formulation with the nanotechnology compound improved dimensional stability significantly by about 12.1%. Meanwhile, other coatings, such as polyethylene, vinyl, melamine, or none, had no appreciable influence on TS under the examined humid conditions (>90%RH). For that case, panel density is a key factor that influences TS [40].

Table 4. Analysis of variance (ANOVA) of multiple regression for the effect of PU coating thickness, different particle size, and board density on the thickness swelling values.

	Model	df	Sum of Squares	Mean Square	F	Sig. ($p \leq 0.05$)
1	Regression	3	65.249	21.750	7.818	0.000 [a]
	Residual	32	89.026	2.782		
	Total	35	154.275			
2	Regression	2	62.263	31.132	11.165	0.000 [b]
	Residual	33	92.012	2.788		
	Total	35	154.275			
3	Regression	1	56.522	56.522	19.659	0.000 [c]
	Residual	34	97.753	2.875		
	Total	35	154.275			
		Coefficient	**Standard Error**	**t Stat**	***p*-Values**	
1	(Constant)	8.234	1.390	5.924	0.000	
	Board density	−0.799	0.556	−1.437	0161	
	Particle size	0.576	0.556	1.036	0.308	
	Coating thickness	−1.535	0.340	−4.507	0.000	
2	(Constant)	9.098	1.113	8.173	0.000	
	Particle size	−0.799	0.557	−1.435	0.161	
	Coating thickness	−1.535	0.341	−54.502	0.000	
3	(Constant)	7.900	0.748	10.566	0.000	
	Coating thickness	−1.535	0.346	−4.434	0.000	

Notes: [a] Predictors: (constant), board density, particle size, PU coating thickness; [b] Predictors: (constant), particle size, PU coating thickness; [c] Predictors: (constant), PU coating thickness.

Table 5. Analysis of variance (ANOVA) of multiple regression for the effect of PU coating thickness, different particle size, and board density on the water absorption values.

	Model	df	Sum of Squares	Mean Square	F	Sig. ($p \leq 0.05$)
1	Regression	3	17,826.556	5942.185	13.429	0.000 [a]
	Residual	32	14,159.997	442.500		
	Total	35	31,986.553			
2	Regression	2	17,639.186	8819.593	20.286	0.000 [b]
	Residual	33	14,347.367	434.769		
	Total	35	31,986.553			
		Coefficient	**Standard Error**	**t Stat**	***p*-Values**	
1	(Constant)	156.876	17.530	8.949	0.000	
	Board density	−4.563	7.012	−0.651	0.520	
	Particle size	−34.512	7.012	−4.922	0.000	
	Coating thickness	−16.980	4.294	−3.954	0.000	
2	(Constant)	150.032	13.901	10.793	0.000	
	Particle size	−34.512	6.950	−4.965	0.000	
	Coating thickness	−16.980	4.256	−3.989	0.000	

Notes: [a] Predictors: (constant), board density, particle size, PU coating thickness; [b] Predictors: (constant), particle size, PU coating thickness.

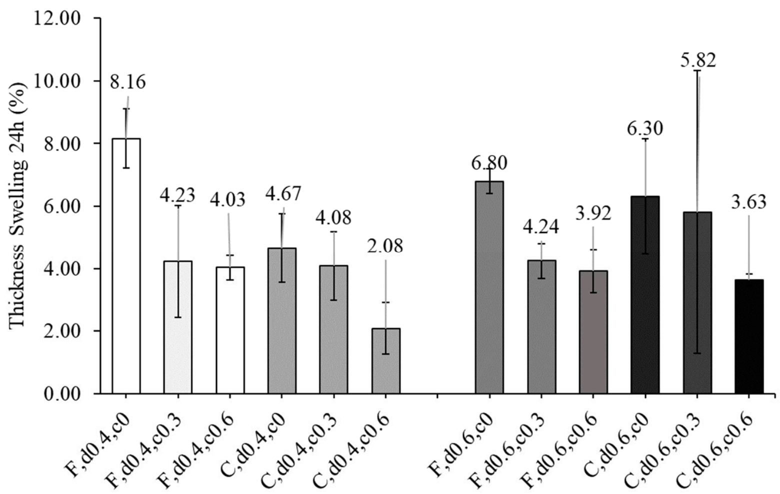

Figure 7. Thickness swelling (TS) 24 h values of bamboo particle board at various PU coating thickness with differences in particle size and board density.

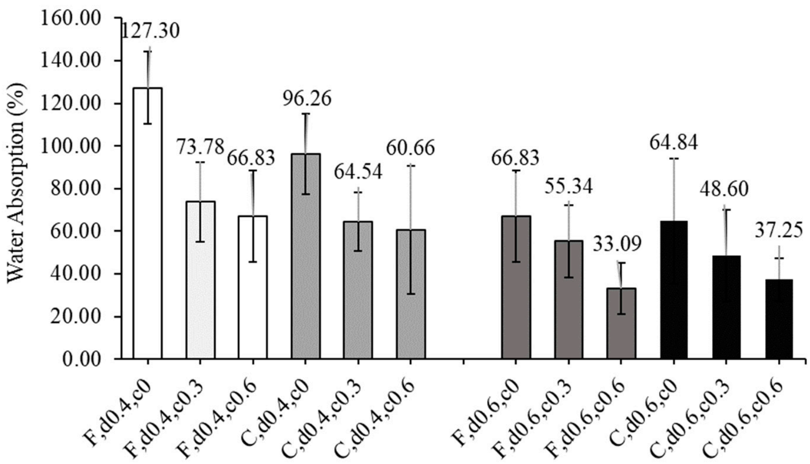

Figure 8. Water absorption (WA) 24 h values of bamboo particle board at various PU coating thickness with difference particle size and board density.

3.2. Acoustical Properties

3.2.1. Sound Absorption

On the uncoated particle board, the sound absorption coefficients of particle boards with varying particle sizes, densities, and coating thicknesses were determined. For both 0.4 g/cm^3 and 0.6 g/cm^3 coarse particle board, sound absorption at frequencies over 2000 Hz was more superior to that of fine particle board of the same density (Figure 9). The effect of panel type (fine or coarse particle board) on absorption at 500–1000 Hz was demonstrated by the fact that the fine particle board performed better at the same density. At frequencies over 1600 Hz, the lower densities had superior sound absorption versus the higher densities and were unaffected by panel type (fine or coarse particle board). At low frequencies up to 500 Hz, values reached approximately 0.1 for all boards and continued to increase to approximately 0.4 at 2000 Hz, with a peak of approximately 0.9 obtained by an uncoated coarse particle board with a density of 0.4 g/cm^3 at frequency 3150 Hz, followed by a fine particle size at the same density for approximately 0.7 (f = 2500 Hz). While at a density of 0.6 g/cm^3, a maximum value of around 0.5 is achieved at a frequency of 2000 Hz. This is consistent with the findings of Iswanto et al. [27], Wong et al. [42], Khair et al. [43], and Karlinasari et al. [12]. Thus, bamboo boards with a density of 0.4 g/cm^3 are found to be effective sound absorbers, with sound absorption greater than half (>0.5).

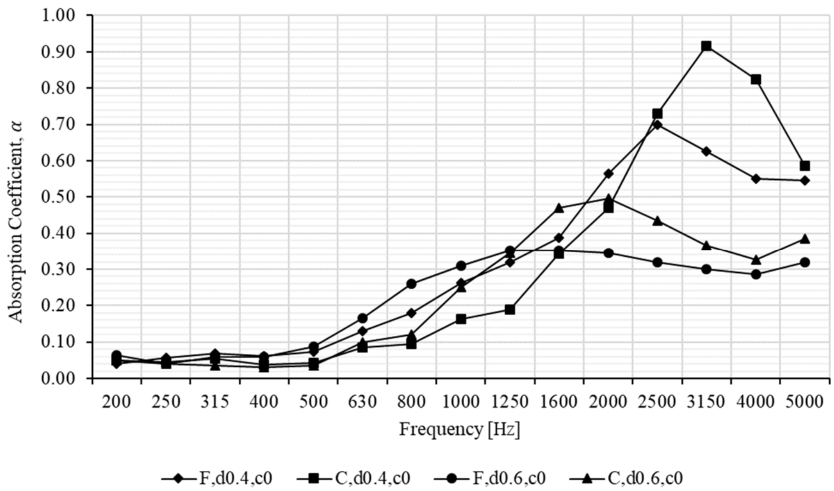

Figure 9. The sound absorption of uncoated particle board bamboos at different particle size and board density.

The effect of coating investigated in this study was on particle board with an acoustic absorption value more than 0.3 at frequencies greater than 1600 Hz. The study differed from prior work on acoustic qualities conducted by Xu et al. [29] and Ivanova et al. [30], which employed solid wood with a sound absorption coefficient of less than 0.3. Coatings can improve the performance and the look of products while also extending their service life and providing qualities specific to their intended application [21]. Both Xu et al.'s [29] and Ivanova et al.'s [30] research concluded that the addition of a polyurethane layer enhances absorption performance, particularly at high frequencies. However, it was shown that the improvement in performance could not surpass 0.3 in terms of sound absorption. Our findings indicate that the addition of a coating significantly lowered high-frequency sound absorption performance (Figure 10). This is because the coating has the ability to seal the pores that absorb sound at high frequencies. These findings offer an overview of the influence of PU coating on porous materials with a high capacity for sound absorption at high frequencies and are novel in comparison to previous research.

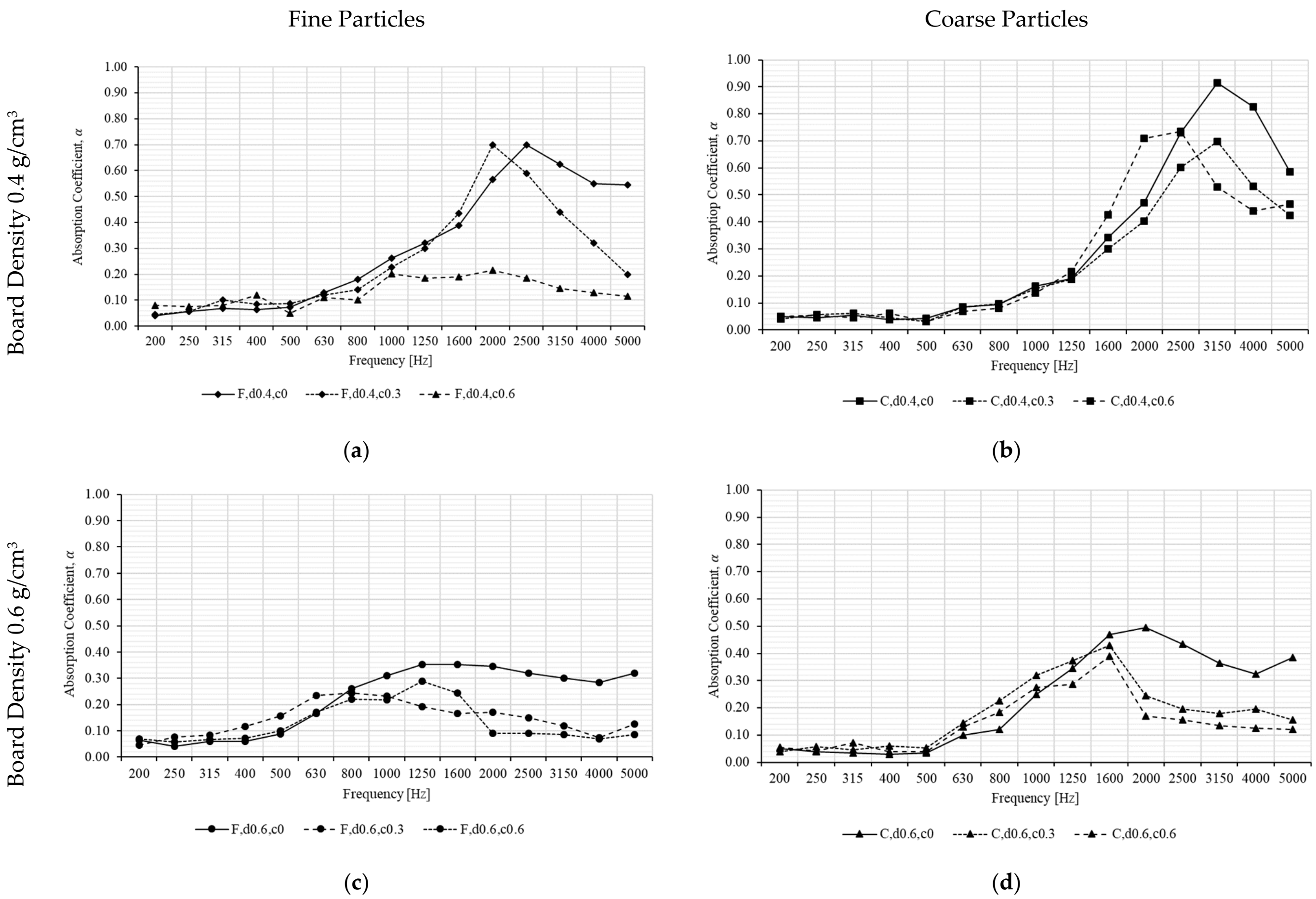

Figure 10. Sound absorption coefficient, α, particle board of various PU coating thickness with difference in particle size and board density at various frequencies: particle board using fine (**a**) and coarse particles (**b**) with board density 0.4 g/cm^3; and particle board using fine (**c**) and coarse particles (**d**) with board density 0.6 g/cm^3.

The presence of a 0.3 mm-thick PU coating improved performance at frequencies of 1600 Hz (0.05 points) and 2000 Hz (0.14 points) in a fine bamboo particle board with a density of 0.4 g/cm^3 (Figure 10a). Performance decline occurred above 2000 Hz, with the highest drop of 0.35 points occurring at 5000 Hz. At frequencies greater than 2000 Hz, the absorption performance declined as the coating thickness increased. The addition of a 0.6 mm thick layer diminishes the absorption performance between 500 and 5000 Hz, dropping to 0.52 points at 2500 Hz.

In coarse board settings with a density of 0.4 g/cm^3 (Figure 10b), it was demonstrated that adding a PU coating of 0.6 mm increased sound absorption capacity by 0.01–0.24 points between 1600–2500 Hz. At frequencies greater than 2000 Hz, the coating performance deteriorated, with the highest drop of 0.39 points happening at 3150 Hz. The addition of a 0.3 mm thick coating reduced the absorption performance between 500 and 5000 Hz. These results were comparable to those obtained when 0.6 mm of coating was applied to fine particle boards.

In general, at a density of 0.4 g/cm^3, the presence of a coating can increases the absorption performance at a frequency of 1600–2000 Hz with coating conditions adjusting to the pore size. When the pore size is small (fine), a coating with a thickness of 0.3 mm is sufficient to provide improved performance, but when the pore size is large (coarse), a thicker coating (0.6 mm) is necessary to provide higher performance. Inadequate coating thickness results in a loss of performance between 500–5000 Hz, with the greatest loss occurs at high frequencies.

For bamboo particle board with a density of 0.6 g/cm^3, the performance was generally below that of particle board with a density of 0.4 g/cm^3, especially at high frequencies. On the fine particle board (Figure 10c), the presence of a 0.3 mm PU coating thickness gave an increase in absorption at a frequency of 250–630 Hz by 0.02–0.07 points. On the coarse particle board (Figure 10d), the increased same performance occurred with the addition of a coating with a thickness of 0.3 mm, even though it occurred at different frequencies. On panels with higher densities, the performance improvement occurred at a lower frequency than on boards with lower densities.

On the coarse particle board, the presence of a 0.3 mm PU coating thickness improved performance at a frequency of 250–1250 Hz with an increase of 0.01–0.11 points. The decrease occurred at frequencies above 1250 Hz with a decrease of 0.04–0.23 compared to the condition without coating. The presence of a 0.6 mm thick coating could improve absorption performance at a frequency of 200–1000 Hz with an increase of 0.01–0.07 points compared to the condition without coating. The decrease in sound absorption occurred at frequencies above 1000 Hz, varying from 0.06 to 0.33 points.

The performance of bamboo particle board with a density of 0.6 g/cm^3 was generally inferior to particle board with a density of 0.4 g/cm^3, particularly at high frequencies. On the fine particle board (Figure 10c), the inclusion of a 0.3 mm PU coating increased absorption by 0.02–0.07 points between 250 and 630 Hz. On coarse particle board (Figure 10d), the same performance improvement occurred with the addition of a 0.3 mm thick layer, but at a different frequency. The performance enhancement occurred at the lower frequency on panels with higher densities than on boards with lower densities.

On coarse particle board, the presence of a 0.3 mm PU coating increased performance by 0.01–0.11 points between 250–1250 Hz. The reduction occurred at frequencies greater than 1250 Hz, with a reduction of 0.04–0.23 points compared to the uncoated condition. A 0.6 mm thick coating can improve absorption performance by 0.01–0.07 points between 200–1000 Hz as compared to the uncoated state. At frequencies greater than 1000 Hz, the sound absorption decreased by 0.06 to 0.33 points.

In general, the particle size type, density, and coating thickness of bamboo particle board influence the sound absorption ability. The presence of a coating reduces the performance of the material at high frequencies and increases it at lower frequencies. The performance decline at high frequencies is bigger (0.02–0.52 points) than the performance increase at low frequencies (0.01–0.24 points decrease). The occurrence of a frequency range with enhanced performance at lower frequencies and decreased performance at higher frequencies is similar with the findings of Ivanova et al. [30], researching scotch pine coating. In comparison to the uncoated samples, those coated with PU demonstrated an increase in performance at 100 Hz and a loss in performance between 630–1400 Hz. The decrease in performance at higher frequencies is greater than the improvement in performance at lower frequencies, which is consistent with the conclusion obtained by Ivanova et al. [30].

The variation in density influences the frequency in which the sound absorption performance increases or decreases. At 0.4 g/cm^3, performance was improved at a greater frequency than at 0.6 g/cm^3, which was 1600–2000 Hz and 1600–2500 Hz for the fine and coarse particle board, respectively. At a density of 0.6 g/cm^3, the fine bamboo particle board performed better at frequencies of 250–1250 Hz, whereas the coarse bamboo panel performed better at frequencies of 200–1000 Hz. Other research has not examined the influence of board density on coating performance in terms of sound absorption. Xu et al. [29] varied the specific gravity, panel thickness, and coating thickness. While Ivanova et al. [30] experimented with coating thickness and the type of coating.

Bamboo panels with an acoustic absorption value greater than 0.3 at frequencies greater than 1600 Hz were used in this study. This is in contrast to the work of Xu et al. [29] and Ivanova et al. [30], who employed solid wood with a sound absorption coefficient of less than 0.3. Both investigations concluded that the inclusion of a PU layer enhanced sound absorption, particularly at high frequencies. However, it turns out that the improvement in performance cannot surpass the absorption coefficient of 0.3.

In our study, we discovered that adding a coating significantly reduces sound absorption performance at high frequencies. This is because of the coating's ability to seal the pores that absorb sound at high frequencies. The construction of the product, the natural properties of the material, the type of surface, density, and porosity characteristics all had an effect on sound absorption [36]. These parameters are associated with sound dissipation through material friction, which allows sound to travel through and be dampened [44]. Our investigation discovers that the thickness of the coating has a substantial effect on the surface roughness, CA, and K value (Table 2). This is most likely due to the board's inadequate capacity to dissipate sound at low and very high frequencies but adequate performance at medium frequencies of 1000–2000 Hz (Figure 9).

3.2.2. Noise Reduction Coefficient

In practice, the sound absorption coefficient is typically expressed as a single value refered to as the noise reduction coefficient (NRC). This is the average sound absorption coefficient at frequencies of 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz following ASTM C243 ASTM 2017). These numbers enable the assumption that the sound absorption coefficient is determined by the material properties and not by the sound field. As a result, the sound absorption coefficient of any material is angle dependent and frequency dependent [36].

The results of this investigation indicate that as particle board density increases, the noise reduction coefficient decreases. At 0.4 g/cm^3 board density, the NRC rose as the PU-coating thickness increased for both fine and coarse particle board, except for fine particle board with 0.6 mm coating thickness. On the other hand, the NRC decreased with increasing thickness of the PU-coating samples at a board density of 0.6 g/cm^3. The lowering value may reach a maximum of 0.07 point (Figure 11). While one material may absorb mostly at low frequencies and another at higher frequencies, both may have comparable NRC values [36]. The ANOVA revealed a substantial difference in the NRC values for each variation (Table 6). This shows that the difference in treatment resulted in a statistically significant change in the NRC value. While there is a significant difference, the treatment for variation in the NRC value was not as extensive as indicated in Figure 11. Additionally, the maximum NRC value in this data set is 0.26 and the minimum is 0.11, indicating that the shift in the NRC value is often small, around 0.15.

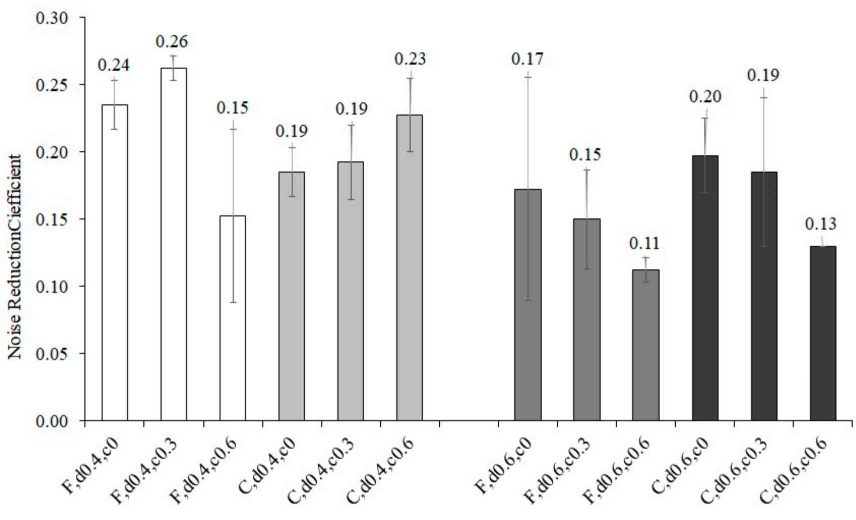

Figure 11. Noise reduction coefficient of various PU coating thickness in fine and coarse particle for 0.4 g/cm^3 and 0.6 g/cm^3.

Table 6. Analysis of variance (ANOVA) of NRC on bamboo particle board which coating treatment.

Source of Variation	df	SS	MS	F	F Crit	*p*-Value
Between Groups	11	0.047446	0.004313	4.726858	2.717331	0.006277
Within Groups	12	0.01095	0.000913			
Total	23	0.058396				

In this context, the application of a surface PU coating is one of the most promising treatments for improving the sound absorption qualities of low-density particle board. However, the layer thickness should be optimized to ensure the desired performance of the surface coating. Coating significantly minimizes the dissipation of results, most likely due to its more homogenous surface.

4. Conclusions

In this work, bamboo particle board coated by polyurethane (PU) lacquer was investigated to evaluate the surface characteristic, thickness swelling, water absorption, as well as acoustical properties of the board. Compared to board density and board particle size, the coating treatment is a dominant factor to improve those board's quality. By adding a PU coating of 0.3 mm and 0.6 mm, the surface roughness significantly decreased up to 80% as well as board's thickness, swelling, and water absorption decreased by about 50% compared with the uncoated boards. A coating increased the acoustical performance of sound absorption at low frequencies (f < 600 Hz), but decreased sharply at higher frequencies (f > 2000 Hz). At the medium frequencies, the coating treatment revealed adequate performance as uncoated boards. Meanwhile, board density seemed to play a more important role in the noise reduction coefficient. For that reason, an optimized coating is a promising treatment to improve acoustical properties, especially in low-density boards.

Author Contributions: Conceptualization, drafting, writing, L.K.; review, editing, supervision, L.K., A.S.S., P.L. and N.N.; Sample preparation, laboratory work, data curation, U.A., Y.A. and A.S.S.; Original draft preparation, U.A.; Formal analysis, A.S.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Indonesia Ministry of Research and Technology (RISTEK)/National Research and Innovation Agency (BRIN) through Research Grants for World Class Research, FY 2021 (contract number: 077/E.4.1/AK.04.PT/2021 and SK 09/E1/KPT/2021).

Data Availability Statement: Not applicable.

Acknowledgments: The authors are grateful for the support of the Indonesia Ministry of Research and Technology (RISTEK)/National Research and Innovation Agency (BRIN) through Research Grants for World Class Research, FY 2021.

Conflicts of Interest: The authors declare no conflict of interest.

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