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Physical, mechanical and hydration kinetics of particleboards manufactured with woody biomass (*Cupressus lusitanica, Gmelina arborea, Tectona grandis*), agricultural resources, and Tetra Pak packages

Róger Moya[1], Diego Camacho[1], Gloria S Oporto[2], Roy F Soto[3] and Julio S Mata[4]

Abstract

Lignocellulosic wastes resulting from agricultural activities as well as Tetra Pak residues from urban centres can cause significant levels of pollution. A possible action to minimize this problem is to use them in the production of particleboards. The purpose of this study was to evaluate the physical, mechanical, and hydration properties of particleboards manufactured with the mixture of woody biomass (*Cupressus lusitanica, Gmelina arborea*, and *Tectona grandis*) and either agricultural wastes [pineapple leaves (*Ananas comosus*) and palm residues (*Elaeis guineensis*)] or Tetra Pak residues (TP). The results show that the particleboards prepared with TP and woody biomass can reduce the swelling and water absorption in up to 40% and 50% compared with particleboards without TP. Also, these particleboards had increased flexure resistance and shear stress (up to 100%) compared with those without TP. On the contrary, particleboards prepared with pineapple leaves in combination with woody biomass showed the lowest mechanical properties, particularly for tensile strength, hardness, glue-line shear, and nail and screw evaluation.

Keywords

Lignocellulosic wastes, particleboards, properties, residues, Tetra Pak, tropical species

Introduction

Tropical regions such as Costa Rica have environmental factors that favour excellent levels of productivity of agricultural crops (Bertsch, 2005). Unfortunately, the residues generated (about 1.5 million tons/year) by this agricultural activity have not been used appropriately (Khalil et al., 2001; Ulloa et al., 2004). These residues can be called as resources. These resources contain basically lignocellulosic components and their limited use has been attributed primarily to a lack of technology for their processing and secondly to the specific application of potential products (Moya et al., 2013).

On the other hand, the variety of packages launched by Tetra Pak generates a large amount of waste residues worldwide and 336 tons/year are generated in Costa Rica. It is reported that about 150 trillion of these packages were produced in 2010 for milk, juice, and other liquid foods (Hidalgo, 2011) and are converted to residues after use. These products decompose slowly and high technology such as plasma treatment is required to recycle these resources (Korkmaz et al., 2009).

The feasibility of using woody biomass in combination with agricultural resources and Tetra Pak residues in particleboard fabrication presents an encouraging challenge and corresponds to the main goal of our current research. It has been reported that approximately 81.5 million m^3 of particleboards were produced in 2004 and their production continues to grow (Saravia-Cortez, 2013).

To date, some research has been performed to add agricultural resources in particleboard fabrication (Grigoriou, 2000; Hidalgo, 2011). Grigoriou (2000) used wheat straw with industrial wood particles in various proportions to fabricate particleboards. The mechanical properties evaluation showed that the partial

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[1] Escuela de Ingeniería Forestal, Instituto Tecnológico de Costa Rica, Cartago, Costa Rica
[2] Division of Forestry and Natural Resources, West Virginia University, Morgantown, WV, USA
[3] Escuela de Química, Universidad Nacional, Heredia, Costa Rica
[4] Escuela de Química, Universidad de Costa Rica, San José, Costa Rica

Corresponding author:
Róger Moya, Escuela de Ingeniería Forestal, Instituto Tecnológico de Costa Rica, CIIBI, Apartado 159-7050; Cartago, Costa Rica.
Email: rmoya@itcr.ac.cr

Table 1. Raw materials used in the fabrication of particleboards.

Woody biomass	Agricultural wastes	Tetra Pak residues
Gmelina arborea *Cupressus lusitanica* *Tectona grandis*	Pineapple leaves (PL): from the crown (PLC), from the plant (PLP) Oil palm residues: empty fruit bunch of oil palm (EBF), oil palm mesocarp fibre of the fruit (OPMF)	Tetra Pak packages (mixture of material) (TP)

Table 2. Summary of the blends utilized in particleboard fabrication.

Woody biomass	Type of residue				
	PLC	PLP	EFB	OPMF	TP
Cupressus lusitánica	50:50 (6)[a]	50:50 (8)	50:50 (8)	50:50 (8)	50:50 (8)
Gmelina arbórea	50:50 (8)	50:50 (6)	50:50 (6)	50:50 (8)	50:50 (8)
Tectona grandis	50:50 (8)	50:50 (6)	50:50 (8)	50:50 (8)	50:50 (8)

Values are the ratio between weight of woody biomass and type of reside (%).
[a] Urea–formaldehyde adhesive used in the particleboard.
See Table 1 for abbreviations.

replacement of wood particles with wheat straw resulted in a reduction of all properties except linear swelling. Belini et al. (2012) demonstrated that panels fabricated with up to 75% bagasse and *Eucalyptus grandis* presented physical and mechanical properties that meet the current specification in Brazil. Hidalgo (2011) presented a preliminary study using recycled Tetra Pak to manufacture composite rigid board using a hot press.

The objective of this study was to evaluate the physical, mechanical, and hydration properties of particleboards prepared with woody biomass growing in tropical areas (*Cupressus lusitanica, Gmelina arborea*, and *Tectona grandis*) in combination with agricultural residues – pineapple leaves (from the crown and the plant) and oil palm (fruit and bunch) – or with discarded Tetra Pak packages.

Materials and methods

Raw materials

Woody biomass corresponded to *C. lusitanica* (CL), *G. arborea* (GA), and *T. grandis* (TG) from plantations (all used for commercial reforestation in tropical countries). Agricultural wastes consisted of pineapple leaves (PL) and residues of oil palm from the extraction of oil empty fruit bunch of oil palm (EFB) and oil palm mesocarp fibre of the fruit (OPMF). PL came from an 18-month-old plantation and they were used from the crown (PLC) and the plant (PLP). Tetra Pak packages residues (TP) were obtained from recycling centres located at Cartago downtown in Costa Rica. Table 1 presents a summary of the raw materials used in the particleboard fabrication.

Material preparation

Pineapple leaves and oil palm resources were dried following the methodology given by Tenorio and Moya (2012) at 60°C. OPMF residues were washed for 1 h in hot water stirring continuously, in order to obtain the best performance with adhesives. TP were washed to eliminate residual contents and then they were cut into 1-cm wide strips using a paper cutter. The three woody species were chipped to size less than 3 cm. Then a Retsch cutting mill was used to reduce the dried chips into particles that resulted in sizes between 0.7 and 6.0 mm. Finally, the particles of each material were placed into a climate-controlled chamber to obtain 6% equilibrium moisture content.

Particleboard preparation

Blends of woody biomass and residues (agricultural and TP packages) used for the particleboard preparation are presented in Table 2. They all were prepared using a 50:50 ratio. The adhesive used was urea–formaldehyde (UF) with 62% solids, and the adhesive application corresponded to between 6 and 8 % with respect to the total weight of the particleboard. The amount of adhesive applied was taken from previous research (Moya et al., 2013). In total, 15 different blends were prepared and 20 35×35 cm boards were obtained from each mixture. The target particleboard density was 0.65 g/cm^3, with an average thickness of 12.5 mm and three layers. The two external layers or faces (2-mm thick) contained fine particles (0.7–1.5 mm long) while the inner layer (core) contained thicker particles (1.5–6.0 mm long). Particleboards were pressed at 25 MPa and 175°C for 10 min and after that they were put into a climate-controlled chamber during 24 h to homogenize the moisture content and to finish the adhesive curing process.

General properties

Particleboard specimens of 2.5 (width) × 2.5 (length) × 1.2 cm (thickness) were cut from each particleboard to measure their thickness, rugosity, and colour. The surface of each particleboard was not sanded, nor did it receive any preparation. Thickness was measured using a micrometre calliper in four places and the mean of the measurements was determined. Rugosity was measured in two different points of the specimens using a Starrett rugosity

Table 3. General properties of the resultant particleboards.

Woody biomass	Residue	Thickness (mm)	Rugosity (µm)	Initial colour			Density (g/cm³)	Moisture content (%)
				L*	a*	b*		
Cupressus lusitanica	PLC	$12.2^{f,g}$	9.1^{e}	$48.2^{e,f}$	4.4^{g}	$21.2^{b,c,d,e}$	$0.68^{b,c,d}$	$11.7^{b,c}$
	PLP	$12.3^{f,e}$	$9.6^{c,d,e}$	$50.5^{d,e}$	$4.9^{g,f}$	$23.2^{a,b,c}$	$0.62^{c,d}$	$11.3^{b,c,d,e}$
	EFB	$12.8^{a,b,c}$	10.4^{a}	$48.2^{e,f}$	6.6^{b}	$21.1^{b,c,d,e}$	0.70^{d}	$11.4^{b,c,d,e}$
	OPMF	13.5^{a}	10.7^{a}	$52.4^{e,c,d}$	$5.7^{b,c,d}$	$22.1^{b,c,d,e}$	$0.63^{c,d}$	$12.4^{a,b,c}$
	TP	$12.3^{e,f,g}$	9.9^{g}	59.9^{a}	$4.7^{f,g}$	$20.4^{g,h}$	$0.64^{b,c,d}$	$9.8^{e,f,g}$
Gmelina arborea	PLC	$12.2^{d,f}$	$9.6^{a,b}$	50.3^{f}	$2.8^{b,c}$	21.1^{a}	$0.68^{a,b}$	$10.6^{a,b}$
	PLP	$12.0^{d,e,f}$	$10.6^{e,d}$	53.2^{f}	$3.3^{d,e,f}$	$23.8^{a,b,c,d}$	$0.65^{a,b}$	$11.4^{d,e,f}$
	EFB	$12.4^{d,e,f}$	$11.6^{e,g}$	48.1^{f}	$5.1^{b,c,d}$	$18.9^{b,c,d,e}$	$0.64^{a,b,c,d}$	$11.3^{b,c}$
	OPMF	$12.2^{d,e,f}$	10.8^{e}	53.8^{f}	4.9^{a}	$20.2^{f,g}$	$0.70^{a,b,c,d}$	$11.4^{b,c}$
	TP	$12.2^{d,f,g}$	$9.5^{a,b}$	62.5^{b}	$3.4^{b,c}$	17.0^{i}	$0.68^{a,b,c}$	$8.9^{f,g}$
Tectona grandis	PLC	$12.7^{a,b,c,d}$	$9.7^{a,b}$	$45.5^{d,e}$	6.1^{h}	$24.1^{e,f,g}$	$0.68^{a,b,c}$	$11.9^{d,e,f,g}$
	PLP	$12.5^{a,b,c,d,e}$	$9.7^{a,b}$	$45.5^{d,e}$	5.3^{h}	$22.6^{a,b}$	$0.64^{a,b,c}$	$11.4^{b,c,d}$
	EFB	$13.0^{a,b}$	$12.0^{a,b,c,d}$	$45.8^{d,e}$	5.9^{h}	$20.5^{g,h}$	$0.68^{a,b,c,d}$	$10.6^{b,c}$
	OPMF	$12.8^{a,b,c}$	$12.4^{a,b}$	$47.1^{c,d}$	$7.5^{f,g}$	$20.7^{g,h}$	$0.66^{a,b,c,d}$	$11.3^{b,c}$
	TP	$12.4^{a,c,d,e,f}$	$10.5^{a,b}$	55.8^{a}	6.2^{h}	16.9^{i}	0.66^{a}	9.1^{g}

Values are means.
Different superscript letters indicate statistically significant differences ($p \leq 0.01$).
L*, a*, b*, coordinates from the CIEL*a*b* colour system; L*, luminosity (position on the black–white axis: 0=black; 100=white); a*, redness (position on the red–green axis: positive, red; negative, green); b*, yellowness (position on the yellow–blue axis: positive, yellow; negative, blue). See Table 1 for other abbreviations.

meter (model no. 3800). Colour was determined using a Hunter Lab mini Scan XE Plus spectrophotometer. This miniscan generated three parameters (L*, a*, and b*) for each measurement using CIEL*a*b* colour system. Coordinate L* indicates luminosity and represents the position on the black–white axis (L*=0 for black, L*=100 for white); coordinate a* indicates redness and represents the position on the red–green axis (positive values for red, negative values for green); and coordinate b* indicates yellowness and represents the position on the yellow–blue axis (positive values for yellow, negative values for blue) (Hunterlab, 1995).

Physical properties

Moisture content (MC) was evaluated according to the ASTM D4442 standard (ASTM, 2012a). Density, dimensional stability measured by dimensional change, swelling (SW), and water absorption (WA) were determined according to the ASTM D1037 standard (ASTM, 2012b); the part-b procedure (24 h in water) was utilized for water absorption.

Hydration kinetic curves. Specimens of 2 × 2 cm and sheet thickness were cut from each particleboard to evaluate hydration. The samples were placed into a container with distilled water to allow saturation of the atmosphere with 100% relative humidity and a temperature of 20°C. The samples were weighed initially and then their weight was recorded every 60 min for a period of 600 min. The values obtained were later used in equation 1 to generate the hydration curves:

$$y = a * t^{b} \tag{1}$$

where y is percentage of hydration, t is time of hydration (min), and a and b are coefficients according to statistical adjustment of the curve.

Mechanical properties. Nine mechanical tests were conducted on the particleboards fabricated. They corresponded to: static bending [to get the modulus of rupture (MOR) and the modulus of elasticity (MOE)]; tensile strength parallel to surface (T//S); tensile strength perpendicular to surface (T⊥S); hardness (HR); glue-line shear (GLS); shear in the plane of the panel (SPS); nail withdrawal (NWI); nail-head pull through (NHP); and direct screw withdrawal (DSW). The ASTM D1037 standard was used in all mechanical properties determinations (ASTM, 2012b).

Statistical analysis

The statistical analysis of the general, physical, and mechanical properties was performed using the one-way ANOVA test to find out significant statistical differences between properties of the particleboards prepared. For those properties that showed significant differences, Tukey test was applied with a significance level of $p<0.05$. For all these analyses, the SAS 8.1 statistics program for Windows (SAS Institute, Cary, NC, USA) was used.

Results

General properties

Thickness, rugosity, colour, density, and MC of the particleboards fabricated are presented in Table 3. Although the target thickness was 12.5 mm, a variation between 12.0 and 13.5 mm was obtained. No significant differences in thickness were found in the particleboards manufactured with GA and TG woody biomass; however, with CL there were statistical differences between some of its blends. Blends composed by both CL and OPMF and CL and EFB presented statistically higher thickness values than those of the remaining CL mixtures, which did not present significant statistical differences.

The evaluation of rugosity of the particleboards showed a variation between 9.1 and 12.4 µm (Table 3). For CL, it was found that particleboard prepared with pineapple leaves from the crown (CL-PLC) and oil palm mesocarp fibre (CL-OPMF) presented statistically higher values of rugosity than those of the other three mixtures of CL. Meanwhile, for GA, differences of rugosity were only found in particleboards prepared with Tetra Pak (GA-TP) and pineapple leaves from the plant (GA-PLC), which were statistically lower than the other three blends. Lastly, no differences between the values of rugosity were found for the five blends of TG (Table 3).

In the evaluation of colour, the values of L*, a*, and b* were higher than zero (Table 3). The L* parameter was statistically higher for the mixtures of the three woody biomass species in combination with TP, while the remaining four blends of each species did not present significant differences. Regarding the a* parameter, for CL particleboards it was found that the mixtures with pineapple (PLP and PLC) presented statistically higher values compared to the mixtures with oil palm and TP. In the case of GA particleboards, the mixtures with oil palm (EFB and OPMF) presented the statistically highest values. Meanwhile, for TG particleboards, the a* value was significantly higher for particleboards with OPMF. Lastly, for the values of b* parameter in CL particleboards, significant differences were only found in the CL-TP mixture, which was significantly lower than the remaining four mixtures. In contrast, GA and TG particleboards gave significantly higher values for b* in the mixtures containing pineapple leaves (PLC and PLP) (Table 3).

Physical properties

The resultant density for the particleboards varied from 0.62 to 0.70 g/cm^3 (Table 3). No significant differences in density were found for particleboards fabricated with the same woody biomass and agricultural or TP resources. In terms of MC, the particleboards presented a variation between 9.1 to 11.9%. All particleboards prepared with TP presented the lowest statistically significant MC values compared to the rest of the mixtures.

Swelling (SW) in the particleboards varied from 20 to 90%. Those panels fabricated with the three woody biomass species and TP presented statistically the lowest SW values (Figure 1a). Particleboards prepared with the woody biomass GA in combination with PLC, EFB, and OPMF presented the highest swelling values (Figure 1a).

Regarding the water absorption (WA) of particleboards, the results varied from 79.5 to 170.8%. Particleboards fabricated with TP presented the lowest values and the highest values corresponded to the particleboards fabricated with PLC. On the other hand, dimensional stability, measured by dimensional change (%), varied from 0.3 to 0.7% in dimension (Figure 1c). The highest values of dimensional change for all particles resulted for woody biomass in combination with OPMF and the lowest dimensional change was presented in particleboards fabricated with TP (Figure 1c).

Hydration kinetics curves

The hydration kinetics curves for each mixture are presented in Figure 2. In all cases, hydration increased with time but at different rates. The particleboards prepared with all three woody biomass types in combination with TP presented the lowest hydration values, not exceeding 2.0% after 500 min exposure. Particleboards prepared with TG attained the equilibrium point in the shortest time compared to all other mixtures; in other words, this species reached equilibrium faster than other species and absorbed less water.

The highest hydration values for all combinations resulted for particleboards prepared with CL and PLC, with a maximum value of hydration of 12% at 500 min exposure. The hydration values of CL in combination PLC resulted 67, 33, and 67% higher than CL in combination with PLP, EFB, and OPMF, respectively. Likely, the hydration values of CL in combination with PLC were 54 and 73% higher than for those particleboards prepared with GA and TG, respectively. The lowest hydration values corresponded to particleboards fabricated with all woody biomass species and TP. The hydration percentages did not exceed 2%.

Mechanical properties

The results for the static bending test, that is MOE and MOR, are presented in Figure 3. CL and TG woody biomass mixed independently with both OPMF and TP demonstrated statistically superior values of MOE and MOR than the rest of the combinations (Figure 3a and 3b). The lower MOR and MOE values were found for GA and TG woody biomass in combination independently with pineapple leaves (PLC and PLP) and EFB (Figure 3a and 3b).

As presented in Table 4, for T//S test in particleboards with CL, the CL-OPMF mixture presented a significantly higher value compared to the other four mixtures, which did not differ from each other. In particleboards with GA, the GA-OPMF mixture was also the highest, while the mixtures with pineapple (PLP and PLC) presented significantly lowest values. Finally, for TG, particleboards prepared with TG-OPMF and TG-TP resulted with significantly highest T//S values (Table 4).

Regarding the HR, only CL in combination with PLC presented a significantly lower HR value compared with all other mixtures. No significant differences were found in HR for particleboards prepared with GA. Finally, for particleboards prepared with TG, the TG-TP, TG-OPMF, and TG-EFB mixtures

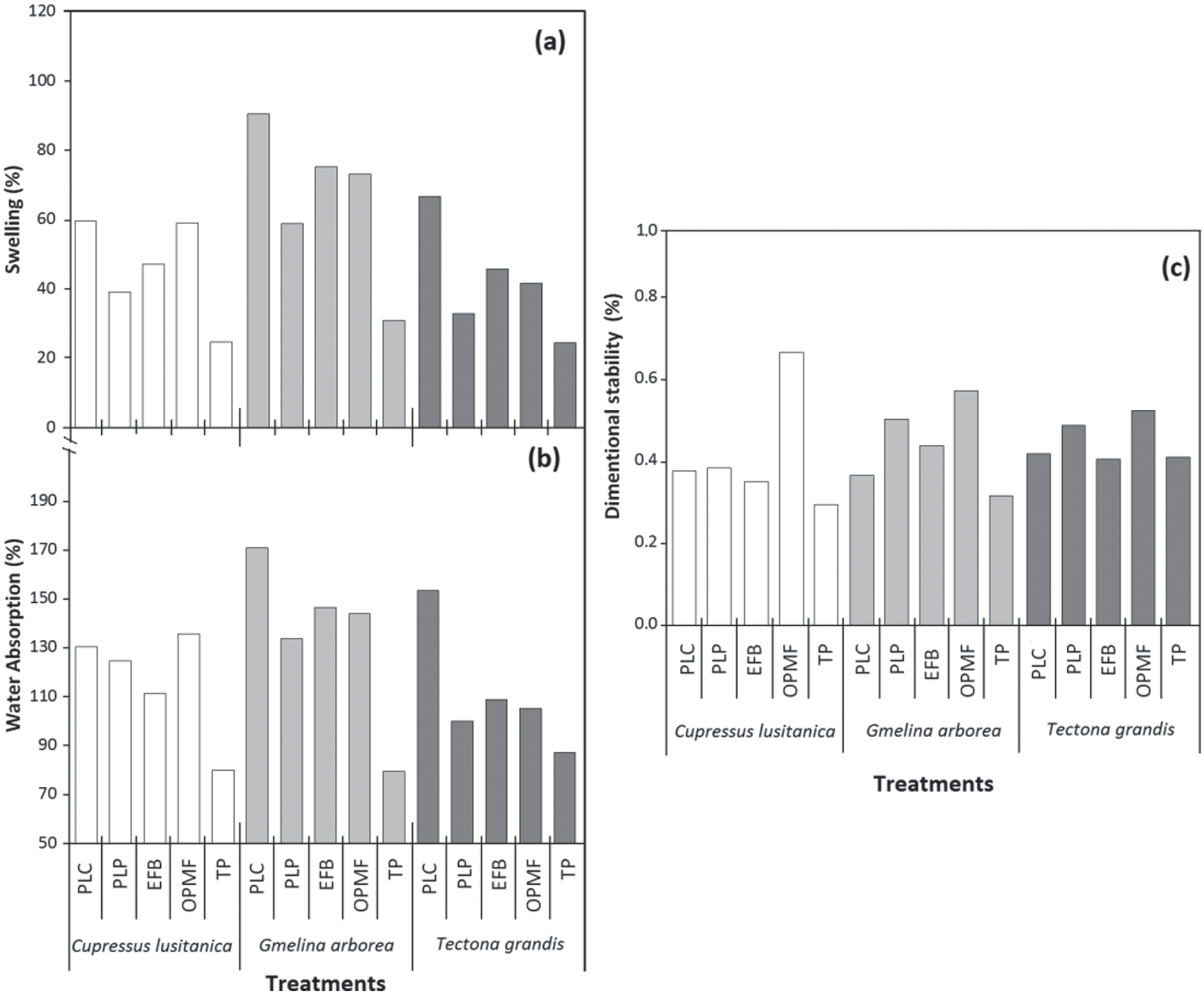

Figure 1. Physical properties [swelling (a), water absorption (b), and dimensional stability (c)] in particleboards manufactured with *Cupressus lusitanica*, *Gmelina arborea*, and *Tectona grandis* mixed with pineapple leaves, fibre from oil palm fruit, and Tetra Pak packages.

presented significantly higher HR values than those of pineapple mixtures.

Regarding the resistance in T⊥S, in particleboards with CL, the CL-TP mixture presented the highest value. For GA, the GA-TP and GA-OPMF mixtures presented higher values of T⊥S compared to the remaining three mixtures. The glue-line shear test (GLS) gave higher resistance for particleboards prepared with TP and two of the woody biomass species: CL and TG. The same trend was found for SPS resistance: i.e. higher values were determined for CL and TG particleboards with TP. The tests involving nails (NWI and NHP) for CL particleboards, the CL-PLC presented the lowest significant value for NWI. No significant differences were found between the mixtures for GA. In the case of TG particleboards, TG-OPMF and TG-TP mixtures had the highest significant values. For the NHP test in CL particleboards, only the CL-PLC mixture showed the lowest significant difference in relation with other mixtures. The GA particleboards mixed with OPMF presented significantly higher nail resistance compared with their remaining mixtures. Finally, TG-OPMF and TG-TP presented significantly higher resistance in NHP. TG-PLP presented the lowest significant resistance in NHP of the TG mixtures (Table 4).

In the DSW test, the particleboards with all three woody biomass types mixed with TP presented significantly higher resistance compared to the mixtures with agricultural residues. The performance of these remaining four agricultural mixtures varied with the woody species used. For particleboards prepared with CL and PLC, the DSW was significantly lower compared to the other mixtures. GA and TG particleboards did not present significant differences in DSW regardless of whether they were made with pineapple leaves or oil palm components (Table 4).

Discussion

The particleboards manufactured in this study had thickness of (mean±standard deviation) 12.75±0.75 mm, slightly higher than the target thickness (12.5 mm). Variations in thickness

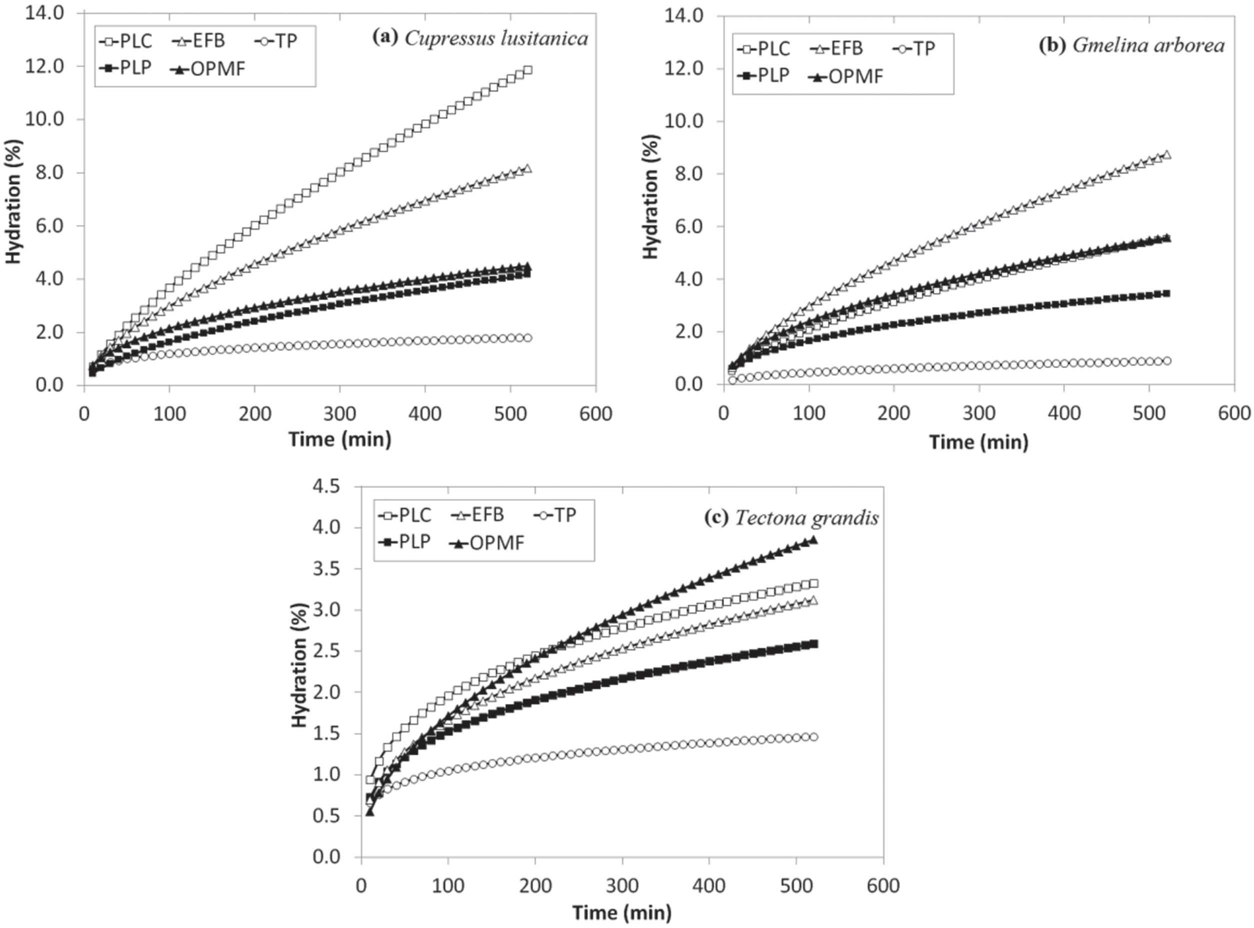

Figure 2. Hydration curves in particleboards manufactured with *Cupressus lusitanica* (a), *Gmelina arborea* (b), and *Tectona grandis* (c) mixed with pineapple leaves, fibre from oil palm fruit, and Tetra Pak packages.

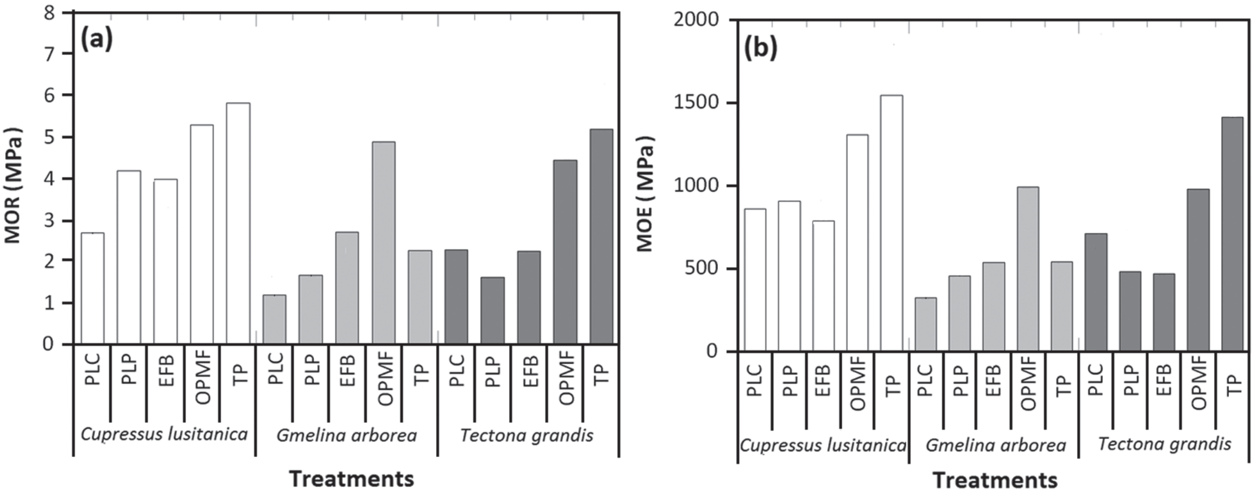

Figure 3. Modulus of rupture (a, MOR) and modulus of elasticity (b, MOE) in static bending tests in particleboards of *Cupressus lusitanica*, *Gmelina arborea*, and *Tectona grandis* (c) mixed with pineapple leaves, fibre from oil palm fruit, and Tetra Pak packages.

will always appear even if the volume of material, pressure, and temperature are programmed to achieve uniform thickness (Halvarsson et al., 2010). The different fibre composition between residues affect pressure applied, thus affecting thickness and microscopic irregularities inside the particleboards are produced, which affects sheet properties (Ratnasingam et al., 2008).

Regarding rugosity, the variation in this study (Table 3) are similar to those values reported by Kalaycioglu et al. (2008) for particleboards manufactured with *Paulownia tormentosa* (i.e.

Table 4. Mechanical properties of particleboards manufactured with *Cupressus lusitanica, Gmelina arborea*, and *Tectona grandis* combined with pineapple leaves, fibre from oil palm fruit, and Tetra Pak packages.

Woody biomass	Residue	T//S (MPa)	HR (kg)	T⊥S (MPa)	GLS (MPa)	SPS (MPa)	NWI (kg)	NHP (Kg)	DSW (kg)
Cupressus lusitanica	PLC	1.1^{e,f}	311^{e}	1.2^{g}	0.9^{c,d}	0.5^{c,d}	2.9^{d}	37.2^{d,e,f,g}	2.9^{c,d,e}
	PLP	1.6^{b,c}	427^{b,c}	2.6^{c,d,e}	0.9^{c,d}	0.5^{b,c}	7.4	43.2^{b,c,d,e,f}	7.4^{b,c}
	EFB	1.9^{b,c}	501^{a,b}	3.3^{b,c}	1.1^{b,c}	0.6^{b,c}	5.9^{b,c}	50.9^{a,b,c,d}	5.9^{c,d,e}
	OPMF	5.0^{a}	468^{a,b}	2.3^{c,d}	0.9^{c,d}	0.5^{b,c}	6.4^{b,c}	56.4^{a,b,c}	6.4^{b,c,d}
	TP	2.6^{b}	401^{a,b}	4.4^{a,b}	1.9^{a}	1.2^{a}	8.0^{b,c}	58.1^{a,b}	8.0^{b,c}
Gmelina arborea	PLC	0.7^{f}	448^{b,c,d}	1.9^{e,f,g}	0.6^{e}	0.4^{c,d}	2.4^{d}	15.8^{h,i}	2.4^{e}
	PLP	0.7^{f}	380^{b,c,d}	1.5^{e,f,g}	0.6^{d,e}	0.4^{c,d}	3.3^{b,c,d}	20.6^{g,h,i}	3.3^{d,e}
	EFB	1.4^{d,e}	453^{a,b}	1.8^{e,f}	1.1^{b,c}	0.5^{b,c}	3.4^{b,c,d}	29.7^{e,f,g,h}	3.4^{d,e}
	OPMF	1.9^{b,c,d}	528^{b,c}	2.5^{c,d}	0.9^{c,d}	0.6^{b,c}	5.9^{b,c}	38.2^{c,d,e,f,g}	4.9^{d,e}
	TP	1.3^{d,e,f}	382^{b,c,d}	2.6^{c,d}	1.0^{c,d}	0.5^{c,d}	4.9^{b,c,d}	10.7^{f,g,h,i}	6.9^{c,d,e}
Tectona grandis	PLC	1.1^{e,f}	367^{d,e}	1.6^{d,e,f,g}	0.7^{d,e}	0.4^{d}	5.1^{b,c,d}	31.3^{h,i}	5.1^{c,d,e}
	PLP	1.1^{e,f}	378^{c,d,e}	1.3^{f,g}	0.7^{d,e}	0.4^{c,d}	5.8^{b,c}	10.7^{i}	5.8^{c,d,e}
	EFB	1.7^{b,c,d}	422^{b}	1.7^{c,d,e,f}	0.8^{c,d}	0.6^{b,c}	4.0^{b,c,d}	31.3^{e,f,g,h}	4.8^{b,c,d,e}
	OPMF	2.3^{a,b}	458^{a,b}	2.4^{c,d,e,f}	1.1^{b,c}	0.8^{b}	8.0^{a,b,c}	50.9^{a,b,c,d,e}	6.3^{b,c,d,e}
	TP	3.0^{a}	413^{a,b}	4.4^{a}	1.6^{a}	1.2^{a}	9.8^{a}	63.0^{a}	9.8^{a}

Values are means.
Different superscript letters indicate statistically significant differences ($p \leq 0.01$).
DSW, direct screw withdrawal; GLS, glue-line shear; HR, hardness test; NHP, nail-head pull through; NWI, nail withdrawal; SPS, shear in the plane of the panel;T//S, tensile strength parallel to surface; T⊥S, tensile strength perpendicular to surface. See Table 1 for other abbreviations.

10.26–12.61 µm). Ratnasingam et al. (2008) reported slightly higher rugosity (13.5–15.0 µm) for EFB particleboards compared to the particleboards performed in this investigation.

The highest values in rugosity and thickness found in particleboards prepared using oil palm residues (EFB and OPMF) may be attributed to variations in density and thickness of the fibre cell walls and the parenchyma that oil palm fruits are composed of (Ratnasingam et al., 2008). Oil palm fibres respond negatively to pressing, for they tend to recover their initial position, thus affecting thickness. In addition, variations in the anatomical elements of the palm create irregularities on the surface, which affects rugosity (Ratnasingam et al., 2008).

With regard to the initial colour, all values of L*, a* and b* were positive, which means that particleboards' colours were combinations of white, red, and yellow shades, respectively. The highest values of L* obtained in particleboards with TP was due to the fact that this material is composed of 60–70% cellulose (Moya et al., 2013), which produces a white colouration and therefore increases the value of L* and reduces values of a* and b*. Particleboards with oil palm and pineapple residues presented higher values of a* and b* due to presence of extractives such as waxes, silica, and metal oxides, and other factors such as pH (Onuorah, 2005), all of which generate oxidation and reduction, processes which result in an increment of both parameters. In relation to colour difference within residues, it was found that a* parameters in CL and pineapple (PLP and PLC) presented statistically higher values compared to oil palm and TP; therefore, pineapple leaf particleboards present more redness than other particleboards fabricated with oil palm. But in the case of GA and TG particleboards, the mixtures with oil palm (EFB and OPMF) were redder than pineapple leaves or TP because their a* parameters were the highest.

Density values varying from 0.62 to 0.70 g/cm^3 were similar to those reported by Kalaycioglu et al. (2008) for particleboards manufactured with *P. tormentosa* (0.55–0.65 g/cm^2). The variation of density is due to homogeneity of processing (Hiziroglu and Kosonkorn, 2006).

In relation to MC, SW, WA, and dimensional stability, there is again little difference between the difference mixtures (Table 3, Figure 1). As regards to particleboards containing TP (regardless of the species with which it is combined), significantly lower values of MC were found, which may be due to the percentage of polyethylene present in the TP material (15–20%; Hidalgo, 2011; Moya et al., 2013). Therefore, particleboards with TP had the best dimensional stability because they had the statistically lowest dimensional changes (Figure 1c). These results were confirmed by hydration kinetics: particleboards with TP presented the lowest hydration values (Figure 2). The presence of plastic in TP reduces the particleboards' capacity to absorb humidity, causing evaporation of the water added in formulation during pressing and heating. Also, polyethylene affects the particleboards' capacity of WA, SW, and hydration curves as this material creates isolation, thus increasing resistance to water absorption. At the same time, it produces higher DSW since absorption in presence of polyethylene differs from absorption without this material.

The mixtures of the three woody biomass species with PLC presented, in general, the highest values of SW, WA, DSW, and hydration curves. This difference may be explained by the higher extractives quantity of pineapple leaves from plant and crown, approximately 30% (Moya et al., 2013), which makes the particleboard more prone to WA and results in increased swelling

(Hiziroglu and Kosonkorn, 2006). Although particleboards prepared with pineapple residues presented higher WA (141%) values compared to oil palm residues and TP, these values are comparable with the values found by Belini et al. (2012) in particleboards manufactured with 50% bagasse and 50% eucalyptus wood.

The GA and TG particleboards combined with TP showed the highest resistance values in static bending test and most of them mechanical properties (Figure 2 and Table 4). On the other hand, the mixtures of the three species with pineapple leaves (PLP and PLC), presented the lowest resistance values in the majority of the mechanical tests, for example HR and NWI. Intermediate values or highest values were found in particleboards manufactured with oil palm residues (e.g. T//S. The different quantity and types of extractives of each kind of agricultural residues might explain the variation in the resulting resistance values. For example, TP contains the lowest amount of extractives than the other residues used, and oil palm and pineapple leaves contain the highest extractive components than the other materials (Moya et al., 2013). To this respect, Grigoriou (2000) mentions that, in order to obtain adequate mechanical properties in particleboards manufactured with wood and any other lignocellulosic material, they must have chemical compatibility. That is, the materials must be used in similar amounts and kind of extractives. The extractives content of the agricultural residues used in this research was studied by Moya et al. (2013). They indicate that more differences in the chemistry and amount of extractive material were found between woody biomass and pineapple leaves.

The chemical nature of TP residues, including cellulose, hydrophobic resin, neutral pH, and lack of extractives (Hidalgo, 2011; Moya et al., 2013) improves the compatibility and enhances curing with urea–formaldehyde adhesives (Han et al., 2008) and results in an increase in the mechanical properties of the particleboards.

Finally, particleboards manufactured with pineapple leaves (PLP and PLC) present the lowest resistance in most of the mechanical tests. And these particleboards present lower physical and mechanical properties than ASTM standard for particleboards (ASTM, 2012a,b). On the contrary, particleboards fabricated with oil palm resources and Tetra Pak packages present good physical and mechanical properties according to ASTM standard. Pineapple leaves are acidic (pH 4.0–4.5; Ayrilmis, 2007); this, combined with their low lignin and cellulose contents plus a high content of extractives, generates little urea–formaldehyde adhesive interaction. It is recognized that acid pH inhibits hydroxyl active groups in cellulose, which are essential for an effective interaction with urea–formaldehyde adhesive (Han et al., 2008).

Conclusions

Woody biomass CL displayed the best mechanical performance compared with GA and TG when it is combined with agricultural wastes or with TP residues. Particleboards prepared with CL and TG in combination with TP residues present improved properties in terms of their lower water absorption, higher dimensional stability, and higher mechanical properties compared to the particleboards prepared with woody biomass and all agricultural wastes. The improvement ranged from 40% in most of the physical properties (water absorption, swelling, dimensional stability) up to 100% in most of the mechanical properties (bending, tensile, hardness, shear, and nail tests). In terms of the particleboards prepared with all three woody biomass types and only agricultural wastes, the best performance was demonstrated for the agricultural waste of OPMF. Conversely, the woody biomass mixtures with pineapple residues presented the lowest performance in most of the mechanical tests.

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Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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