Properties of Composite Wood Panels Fabricated from Eastern Redcedar Employing Various Bio-based Green Adhesives

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Bio-based flours derived from distiller's dried grains with solubles (DDGS), Osage orange seed meal (OOSM), or defatted commercial soybean meal flour-Prolia (PRO) were employed as adhesives with Eastern redcedar (*Juniperus virginiana* L.) wood (ERC) to fabricate composite wood panels (CWPs). OOSM and DDGS were defatted, milled, and screened prior to use. PRO was employed as provided. DDGS, OOSM, or PRO flour were mixed dry with ERC wood to make CWPs using the following conditions: molding temperature of 185 °C, ERC particle sizes of ≤75 μm to 1700 μm, pressure of 5.6 MPa, and employed in flour dosages of 10% to 75%. Flexural properties of DDGS and OOSM flour-ERC composites were similar to composites fabricated using PRO as the resin/adhesive. The dimensional stability properties (water absorption and thickness swelling) of all composites were similar. ERC CWP properties satisfied several European Committee Industry Standards for commercially acceptable CWPs in terms of their flexural properties but were inferior in terms of thickness swelling when subjected to water immersion testing. Surface roughness and color analysis of CWPs were also conducted. Statistical correlations between surface roughness and color properties and the composition of the CWPs were conducted. ERC CWPs were found to have termite resistance.

Keywords: Color analysis; Dimensional stability; Flexural properties; Medium density fiberboard; Surface roughness; Termite resistance

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INTRODUCTION

Eastern redcedar (ERC) (*Juniperus virginiana* L., family Cupressaceae) trees are considered to be an invasive species; they are found in many eastern portions of the United States (Cai *et al.* 2004; Eller and Taylor 2004; Zhang and Hiziroglu 2010; Chotikhun and Hiziroglu 2017). Cedar wood exhibits termite and fungal decay resistance from saproxylic basidiomycete fungi (Eller *et al.* 2010; 2018; Tumen *et al.* 2013; Mankowski *et al.* 2016). These characteristics are attributed to the presence of cedar wood oil (CWO), which suggests that CWO is a natural wood preservative (Tumen *et al.* 2013; Eller *et al.* 2010; 2018). Mature cedar trees provide decorative lumber because of their attractive knotty patterns, but this characteristic detracts from its functionality (Cai *et al.* 2004; Zhang and Hiziroglu 2010).

Engineered wood panels (EWPs) are composite wood panels (CWPs) consisting of an adhesive matrix binding to a wood filler/reinforcement component. EWPs include particleboard (PB), oriented strand board (OSB), medium density fiberboard (MDF), and high density fiberboard (HDF). EWPs are increasingly employed in the construction industry, and their use is predicted to increase by as much as 33% by 2020 (Elling 2015). Several studies have demonstrated that ERC biomass derived from immature wood and waste shavings can be employed in the manufacture of PB (Hiziroglu *et al.* 2002; Lockwood and Cardamone 2002; Cai *et al.* 2004; Hiziroglu and Holcomb 2005; Hiziroglu 2007; Sandak *et al.* 2015; Chotikhun and Hiziroglu 2017). Commercially produced ERC flakeboard is available (DesigntheSpace.com 2018; The Home Depot 2018).

Petroleum-based thermosetting adhesive resins such as urea-formaldehyde (UF) (Lockwood and Cardamone 2002; Cai *et al.* 2004; Melo *et al.* 2014), melamine-formaldehyde (MF) (Mendes *et al.* 2012), or phenol-formaldehyde (PF) (Mendes *et al.* 2012) are typically employed as the binding resins to fabricate FB. These binding resins may cause environmental and health problems due to the emission of volatile organic compounds (VOCs), such as formaldehyde (Kelly 1997; US EPA 2010; CPSC 2013; Chotikun and Hiziroglu 2017). One avenue to address this issue is to substitute these petroleum-based resins with bio-based adhesives such as starch (Chotikhun and Hiziroglu 2017), soybean meal (SBM) flour (Liu and Li 2007; Amaral-Labat *et al.* 2008; Frihart *et al.* 2010, 2014; Gu *et al.* 2013), wheat gluten (Hemsri *et al.* 2012), polylactic acid (Huang *et al.* 2015), or distiller's dried grains with solubles (DDGS) (Tisserat *et al.* 2018a,b). Prior ERC CWPs were fabricated using petroleum-based resins (Lockwood and Cardamone 2002; Cai *et al.* 2004). One of the major disadvantages of employing bio-based adhesives is poor water resistance (Ferdosian *et al.* 2017; Tisserat *et al.* 2018b). Since ERC EWPs are typically employed for interior locations bio-based adhesives may have an application to serve as an adhesive.

The primary objective of this study was to investigate the possibility of employing bio-based seed flours as adhesive/resins to fabricate ERC CWPs. Seed flour proteins are considered to be the primary component in providing adhesive properties for seed flours (Frihart *et al.* 2010; Frihart and Birkeland 2014; Vnučec *et al*. 2016). In the presence of heat and pressure, proteins polymers denature and unfold to form an aggregation that is capable of binding to wood (Frihart *et al.* 2010; Frihart and Birkeland 2014; Vnučec *et al*. 2016). The adhesive properties of three different defatted seed flours were employed: commercial SBM, Prolia (PRO), Osage orange seed meal (OOSM), and DDGS. Soybean meal flour (*e.g.*, PRO) is included in this study because it is the most commonly employed bio-based adhesive used in fabricating CWPs (Frihart *et al.* 2010, 2014; USB 2010; Chotikun and Hiziroglu 2017). Un-defatted SBM contains 40% protein, 20% oil, and 33% carbohydrates (Kaur *et al.* 2017). Osage orange (OO) (*Maclura pomifera* (Raf.) Scheid., family Moraceae) trees are common throughout the eastern US and produce abundant fruit containing numerous seeds. OO seeds contain ~34% protein, 33% oil, and 21% carbohydrates (Tisserat 2018). Currently, OO seeds are processed for industrial oil with the meal discarded (Mitchell 2017). To improve revenues, we sought to develop a use for the seed meal such as an adhesive/resin (Tisserat 2018). Distiller's dried grains with solubles are the solid by-products from ethanol fermentation plants, which are common throughout the Midwest USA. Distiller's dried grains with solubles are composed of ~30% protein, 10% oil, and 54% carbohydrates (Liu 2011). Distillers dried grains with solubles are typically sold as an animal feed, but much evidence suggests they are unhealthy (Gesing 2016; Koeleman 2016). There is a need to find new markets for DDGSs (USGC 2017). Defatted DDGS and OOSM flours express adhesive properties somewhat comparable to PRO (Tisserat *et al.* 2018a,b; Tisserat 2018). Eastern redcedar CWPs prepared without using petroleum-based resins would be entirely biodegradable. Eastern redcedar CWPs prepared with 7% UF resins satisfied or exceeded the minimum industry standards for mechanical properties (Lockwood and Cardamone 2002; Cai *et al.* 2004). In this study, the flexural properties of "all bio-based" ERC CWPs were compared to the industry standards to determine their potential commercial utilization. Several different adhesive flour dosages mixed with ERC wood to fabricate CWPs, and their flexural and dimensional stability properties were assessed. In addition, the physical properties such as the thickness, density, surface roughness, and color analysis of the FB panels was assessed to determine how they are affected by flour/ERC dosages.

A second objective was to determine the adhesive properties of mixing flours derived from two different sources (*i.e.*, DDGS and PRO). Distiller's dried grains with solubles sell for ~\$0.07/lb (~\$0.15/kg), while SBM sells for ~\$0.45/lb (\$1.00/kg) (Alibaba 2018a, 2018b). Combining a low-cost flour (DDGS) with a high-cost flour (PRO) could result in an acceptable hybrid adhesive flour. Such an adhesive flour would be commercially attractive. The third objective of this study was to examine the possibility of employing a solvent-extracted ERC wood as the reinforcement wood for composites. It has previously been found that solvent extracted CWO can provide biocide protection for non-resistant woods (Eller *et al.* 2010). It is unknown how solvent extraction affects the treated ERC wood performance properties. The fourth objective is to test the original ERC CWPs for their biocidal properties. As previously noted, ERC wood exhibits natural biocidal characteristics (Clausen and Yang 2007; Eller *et al.* 2010). In a prior study, ERC FB prepared with 6% or 9% UF exhibited moderate termite resistance (Kard *et al.* 2007). Panels derived from various flour/ERC wood dosages were also tested for termite resistance. It is important to assess how adhesive flour dosages of engineered panels affect the natural biocidal activities of the ERC wood.

EXPERIMENTAL

Materials

Prolia™ (200/90) (PRO) is commercial defatted flour (Cargill Inc., Cedar Rapids, IA, USA). Distillers dried grains with solubles are a commercial animal corn feed product (Archers Daniel Midland Co., Decatur, IL, USA). The OOSM was procured from ground seeds obtained from fruit grown in McLean, Peoria, and Tazewell Counties, Illinois. Distiller's dried grains with solubles and OOSM were defatted with hexane using a Soxhlet extractor. Following defatting, flours were ground with a Thomas-Wiley mill (Model 4, Thomas Scientific, Swedesboro, NJ, USA) using various screens and then sieved using a Ro-Tap™ Shaker (Model RX-29, Tyler, Mentor, OH, USA) employing 203 mm diameter stainless steel #80 mesh to obtain ≤250 µm particles. Prolia™ (200/90) was employed as provided. Defatted PRO, DDGS, and OOSM contained 54%, 30%, and 44% crude protein, respectively.

Eastern redcedar wood was procured from trees grown in Woodford County, Illinois. Sapwood was removed with a bandsaw. The heartwood was subjected to compound miter saw cuts to obtain sawdust. Sawdust then was milled successively through 4-, 2-, and 1-mm screens *via* a Thomas-Wiley mill grinder. Particles were sized employing #12 and #30 US Standard sieves (Newark Wire Cloth Company, Clifton, NJ, USA). The ERC wood portion contained 50% of ≤600 µm particles obtained from particles that passed through the #30 mesh sieve, and 50% 600 µm to 1700 µm particle fraction obtained from particles passing through the #12 mesh sieve and collected on the #30 mesh sieve. In some cases, ERC wood was extracted with hexane or methanol to remove CWO *via* a Soxhlet extractor. The ERC wood contained ~6% moisture.

Table 1. Composite Wood Panel Formulation Weight Percentages

Composition	Matrix (%)	ERC (%)
10,15,25,50,75 DDGS-90,85,75,50,25 ERC	10, 15, 25, 50, 75	90, 85, 75, 50, 25
10,15,25,50,75 OOSM-90,85,75,50,25 ERC	10, 15, 25, 50, 75	90, 85, 75, 50, 25
10,15,25,50,75 PRO-90,85,75,50,25 ERC	10, 15, 25, 50, 75	90, 85, 75, 50, 25
15,50 DDGS/PRO-85,50 ERC	15, 50	85, 50
15,50DDGS/PRO-85,50 ERC/HEX*	15, 50	85, 50
15,50DDGS/PRO-85,50 ERC/MEOH**	15, 50	85, 50

*ERC wood extracted with hexane; **ERC wood extracted with methanol.

Preparations

All panels consisted of 160 g of ingredients. Seed flour dosages of 10%, 15%, 25%, 50%, or 75% of PRO, OOSM, and DDGS were mixed with the balance of ERC wood particles (Table 1). Flour mixtures of equal proportions of DDGS and PRO were combined to create 15% or 50% matrix adhesive portions which were mixed with 85% or 50% native ERC, ERC/HEX, or ERC/MEOH wood portions (Table 1). Seed flour and ERC wood were sealed in a zip-lock bag and mixed for 15 min in a compact dryer (Model MCSDRY1S, Magic Chef, Chicago, IL, USA). Mixed materials were transferred to an aluminum mold (outer dimensions: 15.2 cm W × 30.5 cm L × 5 cm D and mold cavity: 12.7 cm W × 28 cm L × 5 cm D). The mold interior was sprayed thoroughly with mold release (Teflon Dry Spray, Chagrin Falls, OH, USA). Pressings were conducted using manual hydraulic presses (Model 4126, Carver Press Inc., Wabash, IN, USA). The mold was then transferred to a preheated Carver press at 185 °C. Initially, the molds were given 2.8 MPa pressure for 4 min followed by a pressure release, then a press of 4.2 MPa for 4 min followed by pressure release, finally a press of 5.6 MPa for 4 min. Keeping pressure constant at 5.6 MPa, heating was terminated, and water cooling of the press platens commenced. Molds were removed from press when the mold surface reached 27 °C.

Flexural and Physical Tests

Composite panel molds were conditioned at 25 °C and 50% relative humidity (RH) for 72 h. A table saw was used to cut suitable specimen boards to conduct three-point bending tests (EN 310 1993). Panels were 50 mm W × 127 mm L × 3.5 mm to 5.5 mm thick. Five specimen panels of each formulation were tested. Specimen thickness dictates the free span length used to conduct flexural tests with a universal testing machine [Instron Model 1122 (Instron Corp., Norwood, MA, USA)].

Water absorbance (WA) and thickness swelling (TS) were conducted on 50 mm × 50 mm squares submerged for 24 h according to EN 317 (1993) standards.

Color measurements of 5 locations on samples panels were made using a Chroma Meter CR-400 spectrophoto-colorimeter (Konica Minolta, Ramsey, NJ, USA). The scanner was calibrated with a white tile. With this coordinate system, the L^* value [lightness [brightness, ranging from 0 (black) to 100 (white)]; the a^* value [redness or green-red coordinate, ranging from -100 (green) to +100 (red)]; the b^* value [yellowness or green-red coordinate,[ranging from -100 (blue) to +100 (yellow))); the C^*_{ab} value (chromaticity, color saturation); and H^*_{ab} (Hue angle, tonality angle)]. C^*_{ab} and H^*_{ab} values are derived using the formulas: $\sqrt{(a^{*2} + b^{*2})}$ and arctan (b^*/a^*), respectively.

Surface roughness properties were measured with Model SJ-210 (Mitutoyo Corp., Kanagawa, Japan) surface tester fitted with a stylus profile detector. Average roughness (R_a), mean peak-to-valley height (R_z), and maximum roughness (maximum peak-to-valley height) (R_y) were calculated according to ISO 4287 (1997). Five surface roughness readings for each panel were conducted. Tester specifications were: speed: 0.5 mm/s, pin diameter: 10 μm, pin angle: 90°, tracing line (L_t) length: 12.5 mm, cut-off (λ_x): 2.5 μm, and scanning arm measuring force: 4 mN. Prior to tests, the detector was calibrated and all tests were performed at room temperature (25 °C ± 2 °C).

Wood and matrix ingredients and molded panels were photographed with a digital camera fitted with a 5× optical/2× digital zoom lenses (Model # DSCF707 Cyber-shot 5 MP, Sony Corp., Tokyo, Japan). Surface and sawn cross sections of panels were examined and photographed.

Termite Resistance Tests

Composite panels were tested for termite resistance employing a no-choice test (*i.e.*, only one treatment per container) with eastern subterranean termites (*Reticulitermes flavipes* Kollar, 1837; Blattodea: Rhinotermitidae) according to AWPA E1-17 (2017) with a slight modification for test jar moisture content. Soldiers and worker termites were collected from dead logs located at the Sam D. Hamilton Noxubee National Wildlife Refuge (Starkville, Mississippi) and kept in the darkness in cut log sections sealed in 30-gallon trash cans. Screw-top jars were filled with 150 g sand along with 20 mL distilled water and equilibrated for 2 h.

Bio-composite panels and control Southern Pine (SP) 20 mm W × 20 L × 5 mm D wood wafers were conditioned (33 °C, 62% ± 3%), weighed and placed on a square of foil on top of the damp sand with one block in each jar. Termites were collected from log sections the day of the test by opening the rotting wood and shaking the termites from the wood through a screen to catch large debris. Termites were then placed in plastic tubs containing moistened towel paper for 2 h, counted and transferred into jars using an aspirator. A total of 400 termites (396 workers and 4 soldiers) were transferred into each jar and kept in a conditioning chamber at 27 °C and 75% ± 2% relative humidity for 28 d. After four weeks, the number of live termites were counted. Test samples were brushed to remove sand, conditioned for one week, and re-weighed to determine weight loss as described in AWPA E1-17 (2017). Sample weight loss and termite mortality were recorded after a 28 d exposure to the termites. Six replications of each treatment were conducted.

Statistical Analysis

Experimental data were analyzed using the Duncan's Multiple Range Test ($p \leq 0.05$) (Statistix 9, Analytical Software, Tallahassee, FL, USA). As applicable, Pearson correlations coefficients compared various variables.

RESULTS AND DISCUSSION

Influence of Matrix and ERC Dosages on the Flexural Properties of CWPs

The physical, flexural, and dimensional stability properties of composites employing the various DDGS-ERC, OOSM-ERC, and PRO-ERC dosages are given in Table 2. Composites that contained higher densities produced panels that had lower thickness. Pearson correlation coefficients comparing the physical, flexural, surface roughness, and dimensional stability properties of all composites are shown in Table 3. Significant correlations occurred between panel density and panel thickness properties and flexural properties. Increasing the concentration of wood in the ERC CWPs (*i.e*., 10:90, 15:85, and 25:75 matrix-ERC (%.wt) composites) resulted in a reduction of flexural properties compared to lowering the wood concentration and increasing the matrix portion concentration (*i.e*., 50:50 and 75:25 matrix-ERC (%.wt) composites. The highest flexural properties were obtained from composites containing 50:50 matrix-ERC (%.wt). The DDGS-ERC composites had lower flexural properties compared to PRO-ERC and OOSM-ERC composites (Table 2).

According to the European Committee for Standards, the nominal flexural and TS properties for interior use CWPs (PB, MDF, and HDF) are given in Table 3. The density of the ERC CWPs varied greatly and was closely associated with the matrix concentration employed. ERC CWPs exhibited densities that were relatively high compared to commercial CWPs, ranging from 860 to 1290 $kg{\cdot}m^{-3}$. Densities of commercial PB, MDF and HDF range considerably and are reported at 160 to 800 $kg{\cdot}m^{-3}$, 450 to 800 $kg{\cdot}m^{-3}$, and 600 to 1450 $kg{\cdot}m^{-3}$, respectively (Cheng *et al*. 2004; Uzochukwu 2017; Doityourself.com, 2019). On this basis, ERC CWPs can be considered to be a type of PB, MDF, or HDF. The flexural properties of several ERC composites satisfy these requirements (Table 1). The flexural properties of the PRO-ERC composites were generally higher than the OOSM-ERC and DDGS-ERC composites. However, the 50OOSM-50ERC and 75OOSM-25ERC composites were on par with the 50PRO-50ERC and 75PRO-25ERC composites.

It is generally accepted that the protein component of the flour is responsible for its adhesive properties (Frihart *et al.* 2010, Frihart and Birkeland 2014). Distiller's dried grain with solubles, OOSM, and PRO contain 30%, 44%, and 54% protein, respectively (Tisserat *et al.* 2018a,b; Tisserat 2018). Bio-adhesives are composed of different protein types, which could also contribute towards its adhesive properties (Tisserat *et al.* 2018a). The lower protein concentrations are probably responsible for the inferior performance of DDGS composites when compared to OOSM and PRO composites. In a prior study, employing Paulownia wood (PW) as the reinforcement wood, DDGS-PW composites were found to have flexural properties similar to PRO-PW composites, suggesting that the wood species used in the composite has a large influence on its flexural properties (Tisserat *et al.* 2018b). In this study, employing ERC wood, the DDGS CWPs were inferior to PRO and OOSM CWPs. Apparently, PW has a greater ability to bind with DDGS than ERC. Nevertheless, it should be noted that the DDGS composites exhibited flexural properties that exceeded the nominal European Committee for Standards for fiberboard flexural properties.

Mixing PRO and DDGS to develop a less expensive soy flour adhesive produced an adhesive with flexural properties that was superior to using DDGS alone and was only slightly inferior to employing PRO only (Table 2). The hybrid matrix composites 15DDGS/PRO-85ERC had MOR and MOE values of 17.5 and 2235, respectively. By comparison, the 15DDGS-85 ERC and 15PRO-ERC had MOR and MOE values of 14.9 and 2134 and 25 and 2748, respectively. However, the 50DDGS/PRO-50ERC composite had flexural properties on par with 50PRO-50ERC (Table 2).

Table 2. Physical, Flexural, and Dimensional Stability Properties of CWPs Utilizing DDGS, OOSM, or PRO Flours Reinforced with ERC Wood*

Composition	Thickness (mm)	Density (kg·m³)	MOR (MPa)	MOE (MPa)	WA (%)	TS (%)
10DDGS-90ERC	4.5 ± 0.08a	860 ± 19a	9.4 ± 0.9a	1688 ± 142a	165 ± 13a	107 ± 8a
15DDGS-85ERC	4.3 ± 0.06a	924 ± 7b	14.9 ± 0.8b	2134 ± 127b	123 ± 4b	88 ± 3b
25DDGS-75ERC	3.9 ± 0.05b	1043 ± 17c	25.0 ± 1.0c	3816 ± 216c	84 ± 8c	69 ± 5c
50DDGS-50ERC	3.4 ± 0.08c	1239 ± 19d	25.2 ± 0.5c	4063 ± 131c	37 ± 2d	36 ± 1d
75DDGS-25ERC	3.1 ± 0.09c	1303 ± 38e	22.6 ± 0.9c	3771 ± 142c	33 ± 5d	35 ± 1d
10OOSM-90ERC	4.9 ± 0.06d	835 ± 17a	14.9 ± 0.6b	1963 ± 28b	131 ± 11b	79 ± 4b
15OOSM-85ERC	4.8 ± 0.08d	865 ± 12a	16.9 ± 1.5b	2183 ± 106b	104 ± 4e	66 ± 3c
25OOSM-75ERC	4.4 ± 0.05a	927 ± 12b	25.7 ± 2.5c	2875 ± 193d	59 ± 10f	56 ± 3c
50OOSM-50ERC	3.7 ± 0.06b	1142 ± 25f	32.3 ± 1.5d	4316 ± 250c	38 ± 4d	36 ± 3d
OOSM-ERC 75-25	3.4 ± 0.05c	1271 ± 17d	31.6 ± 0.8d	4888 ± 134e	35 ± 2d	32 ± 1d
10PRO-90ERC	4.4 ± 0.04a	910 ± 10b	21.0 ± 0.9c	2315 ± 67b	80 ± 3c	48 ± 2e
15PRO-85ERC	4.4 ± 0.07a	930 ± 16b	25.0 ± 1.7c	2748 ± 144d	70 ± 5c	44 ± 2e
25PRO-75ERC	3.9 ± 0.09b	1057 ± 26c	32.9 ± 1.2d	3818 ± 227c	49 ± 5f	37 ± 3d
50PRO-50ERC	3.5 ± 0.03c	1236 ± 16d	32.8 ± 0.8d	4571 ± 70e	39 ± 1d	33 ± 1d
75PRO-25ERC	3.3 ± 0.12c	1291 ± 20e	26.2 ± 0.8c	4338 ± 76c	49 ± 3f	45 ± 2e
15DDGS/PRO-85ERC	4.6 ± 0.06a	936 ± 12b	17.5 ± 0.7b	2235 ± 77b	93 ± 5ce	58 ± 1c
50DDGS/PRO-50ERC	3.4 ± 0.03c	1284 ± 14d	36.0 ± 1.1d	4729 ± 156e	31 ± 1d	32 ± 1d
15DDGS/PRO-85ERC/HEX	4.7 ± 0.11a	920 ± 11b	12.7 ± 1.3b	1765 ± 212ab	117 ± 4b	75 ± 5b
50DDGS/PRO-50ERC/HEX	3.4 ± 0.11c	1283 ± 17d	31.3 ± 2.6d	4522 ± 403ce	37 ± 1d	35 ± 1d
15DDGS/PRO-85ERC/MEOH	5.3 ± 0.11f	811 ± 9g	7.0 ± 0.4e	1336 ± 67f	156 ± 3a	76 ± 2b
50DDGS/PRO-50ERC/MEOH	3.7 ± 0.07b	1177 ± 19f	33.3 ± 1.4d	4659 ± 215e	44 ± 3f	38 ± 1d

*Means and standard errors (n = 5) within a column with different letters are significantly different (P ≤0.05).

Table 3. Range of European Standards for Nominal Properties of CWPs Used in Various Interior Dry/Humid Conditions*

Specifications*	MOR	MOE	TS
(Description, thickness)	(MPa)	(MPa)	(%)
PB, 3 mm to 6 mm	13 - 20	1800 - 2550	14 - 23
MDF, >2.5 mm to 6 mm	23 - 34	2700 - 3000	18 - 35
HB, >3.5 mm to 5.5 mm	30 - 44	2500 - 4500	10 - 35

*Values for PB, EN 312 (2003); MDF, EN 622-5 (2006) and HB, EN 622-2 (1993).

CWPs fabricated with an adhesive consisting of equal parts DDGS and PRO at low concentrations (*i.e.*, 15%) exhibited an increase in MOR and MOE values of 17% and 5%, respectively, *versus* CWPs employing DDGS only at the same concentration. However, CWPs fabricated with high concentrations of equal parts DDGS and PRO (*i.e.*, 50%) exhibited an increase in MOR and MOE values of 30% and 16%, respectively, *versus* CWPs employing DDGS alone at the same concentration (Table 2).

Treatment of ERC wood with solvents to remove CWO resulted in composites that were inferior to non-treated wood. The MOR and MOE values of 15DDGS/PRO-ERC/HEX, 15DDGS/PRO-ERC/MEOH and 15DDGS/PRO-ERC were 12.7 and 1765, 7 and 1336, and 17.6 and 2235, respectively. However, when the matrix concentration was tested at 50% DDGS/PRO their composite flexural properties were all the same regardless of the wood type employed. This observation suggests that the matrix concentration is more significant than the wood treatment to create a composite with high flexural properties (Table 2).

Dimensional Stability of CWPs

Increasing the concentration of the adhesive matrix in the CWPs causes an improvement in the dimensional stability properties (Table 2). Overall, the lowest WA and TS values occurred when the CWPs contained 50% or 75% matrix. This can be attributed to the increased cohesion caused by the binding of the matrix to the wood portions (Pan *et al.* 2006; Tisserat *et al.* 2018a, 2018b).

The carbohydrate content of the CWP can influence its dimensional stability. Carbohydrates are noted for their poor water resistance in CWPs (Frihart and Birkeland 2014). In addition, water adsorption and TS values were influenced by the matrix type employed. For example, 10DDGS-90ERC composites exhibited WA and TS values of 165% and 107%, respectively. On the other hand, 10PRO-90ERC composites exhibited WA and TS values of 80% and 48%, respectively. CWPs composed of DDGSs have less protein and more carbohydrates than CWP composed of PRO. This also suggests that less cohesion occurred between the matrix and the wood for the 10DDGS-90ERC composite compared to that of the 10PRO-90ERC composite. As shown in Table 4, significant Pearson correlation coefficient values occurred between WA and TS values and the thickness, density, MOR, and MOE values. The European Committee for Standards nominal properties for CWPs with thickness of 3 mm to 6 mm for TS values are: PB, 14% to 23%; MDF, 18% to 35%; and HB, 10% to 35% (Table 3). Several ERC CWPs satisfied these nominal properties (Tables 2 and 3).

Table 4. Pearson Correlation Coefficient Values for Physical, Flexural, and Dimensional Stability Properties for all ERC CWPs*

Correlations:	Thickness (mm)	Density ($Kg{\cdot}m^{-3}$)	MOR (MPa)	MOE (MPa)	R_a (µm)	R_z (µm)	R_y (µm)	WA (%)	TS (%)
Thickness (mm)	--	-0.986	-0.661	-0.897	0.868	0.873	0.883	0.799	0.699
Density ($Kg{\cdot}m^{-3}$)	-0.986	--	0.659	0.909	-0.867	-0.891	-0.899	-0.804	-0.720
MOR (MPa)	-0.661	0.659	--	0.879	-0.771	-0.733	-0.777	-0.894	-0.873
MOE (MPa)	-0.897	0.909	0.879	--	-0.868	-0.876	-0.895	-0.871	-0.796
R_a (µm)	0.868	-0.867	-0.771	-0.868	--	0.978	0.990	0.800	0.756
R_z (µm)	0.873	-0.891	-0.733	-0.876	0.978	--	0.993	0.769	0.744
R_y (µm)	0.883	-0.899	-0.777	-0.895	0.990	0.993	--	0.819	0.782
WA (%)	0.799	-0.804	-0.894	-0.871	0.800	0.769	0.819	--	0.965
TS (%)	0.699	-0.720	-0.873	-0.796	0.756	0.744	0.782	0.965	--

*All compared values were significant (P = 0.05), employing 5 replicates

Surface Roughness Properties of CWPs

Table 5 shows the surface roughness properties of various ERC CWPs. CWPs containing high concentrations of ERC wood invariably exhibited higher surface roughness values. Conversely, the inclusion of higher matrix concentrations (*i.e.*, 50% or 75%) resulted in lower surface roughness values. Surface roughness represents the surface properties (*i.e.*, appearance, feel, interaction to additives or over-layments) (Rolleri and Roffael 2010). Surface roughness is related to the size and frequency of the surface quality, which is caused by fine irregularities on a surface. Rolleri and Roffael (2010) consider R_a values to represent the most important property in surface roughness analysis. It is notable that ERC CWPs containing bio-based adhesives exhibited R_a values (*e.g.*, 0.5 µm to 3.5 µm) that were considerably less than spruce or Douglas fir PBs (*e.g.*, 5.2 µm to 11.2 µm) utilizing UF adhesives (Rolleri and Roffael 2010). ERC PB prepared with 9% UF resin and 91% ERC wood exhibited 14.6 µm R_a values. Wood plastic composites of 50% wood flour and 50% polypropylene exhibited R_a values of ~3.4, which is on par with the ERC CWPs (Ayrilmis *et al.* 2012). Bio-based adhesives can provide a relatively smooth surface compared to those found in other CWPs fabricated with plastic resins or petroleum-based resins. Because bio-based panels are hygroscopic, their dimensional stability values vary with the extent of cohesion occurring between the binding agent portion and the reinforcement wood portion (Ulker 2018). Surface roughness values provide a means of quickly evaluating how bio-based panels will react in wet, humid, or immersed water environments (Ulker 2018). Wood panels with a high frequency of surface irregularities will exhibit high surface roughness properties and correspondingly poorer dimensional stability properties (Hiziroglu 2007; Ulker 2018). As shown in Tables 2, 4, and 5, CWPs containing the low percentages of bio-adhesives exhibited higher surface roughness properties and conversely lower flexural properties and dimensional stability properties. Significant Pearson coefficients occurred between all these properties (Table 4), indicating close relationships between themselves.

The removal of CWO from ERC wood to provide a bio-based wood preservative has been studied (Eller and Taylor 2004; Eller *et al.* 2010; Mankowski *et al.* 2016). The remaining extracted ERC wood was employed as a reinforcement wood for bio-based panels. It is important to understand how the extraction of CWO from ERC wood affects its functionality as a wood reinforcement in bio-based panels in order to use it as a commercial ingredient in CWPs.

Table 5. Surface Roughness Properties of Various ERC CWPs

Description	R_a (µm)	R_z (µm)	R_y (µm)
10DDGS-90ERC	2.9 ± 0.16a	12.7 ± 0.56a	21.2 ± 1.06a
15DDGS-85ERC	3.4 ± 0.31a	16.8 ± 1.41b	24.5 ± 1.71a
25DDGS-75ERC	2.9 ± 0.75a	12.2 ± 2.75af	19.6 ± 3.9a
50DDGS-50ERC	1.2 ± 0.07b	5.1 ± 0.64c	7.9 ± 0.94b
75DDGS-25ERC	0.9 ± 0.12b	3.4 ± 0.30d	5.14 ± 0.50c
10OOSM-90ERC	4.6 ± 0.60c	17.8 ± 1.93b	28.1 ± 3.17a
15OOSM-85ERC	3.1 ± 0.20a	12.9 ± 0.95a	20.2 ± 0.95a
25OOSM-75ERC	3.1 ± 0.47a	16.0 ± 3.14b	21.4 ± 2.89a
50OOSM-50ERC	0.5 ± 0.04d	2.1 ± 0.19e	3.3 ± 0.4d
75OOSM-25ERC	0.7 ± 0.13b	2.6 ± 0.50de	3.8 ± 0.47d
10PRO-85ERC	3.5 ± 0.48a	15.9 ± 2.32b	24.3 ± 2.71a
15PRO-85ERC	2.0 ± 0.23a	10.0 ± 1.03f	15.5 ± 1.11e
25PRO-75ERC	0.7 ± 0.06b	4.4 ± 0.93cd	5.8 ± 0.93c
50PRO-50ERC	0.9 ± 0.04b	3.3 ± 0.13d	4.7 ± 0.18c
75PRO-25ERC	0.8 ± 0.18b	3.0 ± 0.71d	4.4 ± 1.08cd
15DDGS/PRO-85ERC	3.9 ± 0.7a	18.8 ± 2.9b	24.7 ± 3.4a
50DDGS/PRO-50ERC	0.8 ± 0.1b	2.8 ± 0.3de	4.4 ± 0.5c
15DDGS/PRO-85ERC/HEX	6.6 ± 0.7e	29.8 ± 2.8g	41.1 ± 3f
50DDGS/PRO-50ERC/HEX	0.6 ± 0b	2.4 ± 0.2e	3.9 ± 0.4c
15DDGS/PRO-85ERC/MEOH	4.7 ± 0.7c	20.4 ± 3.1b	28.8 ± 4.2a
50DDGS/PRO-50ERC/MEOH	0.5 ± 0.1b	3 ± 1.1de	4.1 ± 1.1c

*Means and standard errors (n = 5) within a column with different letters are significantly different (P ≤0.05).

Solvent extracted ERC wood composites (*i.e.*, 15DDGS/PRO-85ERC/HEX and 15DDGS/PRO-85ERC/MEOH) exhibited considerably higher surface roughness values compared to unextracted ERC wood composites (*i.e.*, 15DDGS/PRO-85ERC) (Table 5). Simultaneously, the flexural properties of solvent extracted ERC wood composites were considerably inferior to those of unextracted ERC wood composites (Table 2). As shown in Table 4, significant Pearson coefficients occurred between the surface roughness, physical, flexural, and dimensional stability values. It is clear that extracted ERC wood causes considerable changes in the surface roughness, flexural, and dimensional stability properties of the CWPs especially when low concentrations of bio-adhesives were employed (*i.e.*, 15DDGS/PRO-85ERC/HEX and 15DDGS/PRO-85ERC/MEOH). However, such changes did not occur when higher concentrations of bio-bases adhesives were employed (*e.g.*, 50DDGS/PRO-50ERC/HEX and 50DDGS/PRO-50ERC/MEOH).

Color Analysis of CWPs

One the most important characteristic of ERC wood is its attractive red color (Cai *et al.* 2004; DesigntheSpace 2018; The Home Depot 2018). The color properties of ERC wood, bio-based matrices, and CWPs are shown in Table 6. The lightness (L^*), green-red coordinates (a^*) and blue-yellow coordinates (b^*), and chromaticity (color saturation) of the wood were dramatically altered depending on the concentration of the matrix and wood reinforcement components (Fig. 1; Table 6 and 7). Increasing the concentration of the bio-based adhesives resulted in darkening of the wood and significant decreases in lightness, redness, yellowness, and chromatic properties (Table 5). The H^* values were less affected by matrix concentration. For example, 10DDGS-90ERC and 50DDGS-50ERC composites exhibited L^*, a^*, b^*, and C^*_{ab} values of: 47, 13, 11, and 18; and 27, 7, 7, and 10, respectively. Pearson coefficients comparing the matrix and wood concentrations and color properties are given in Table 6. There were significant correlations between the matrix percentages and L^*, a^*, b^*, and C^*_{ab} coordinates. However, there were no observed correlations between the H^* values and the other values measured.

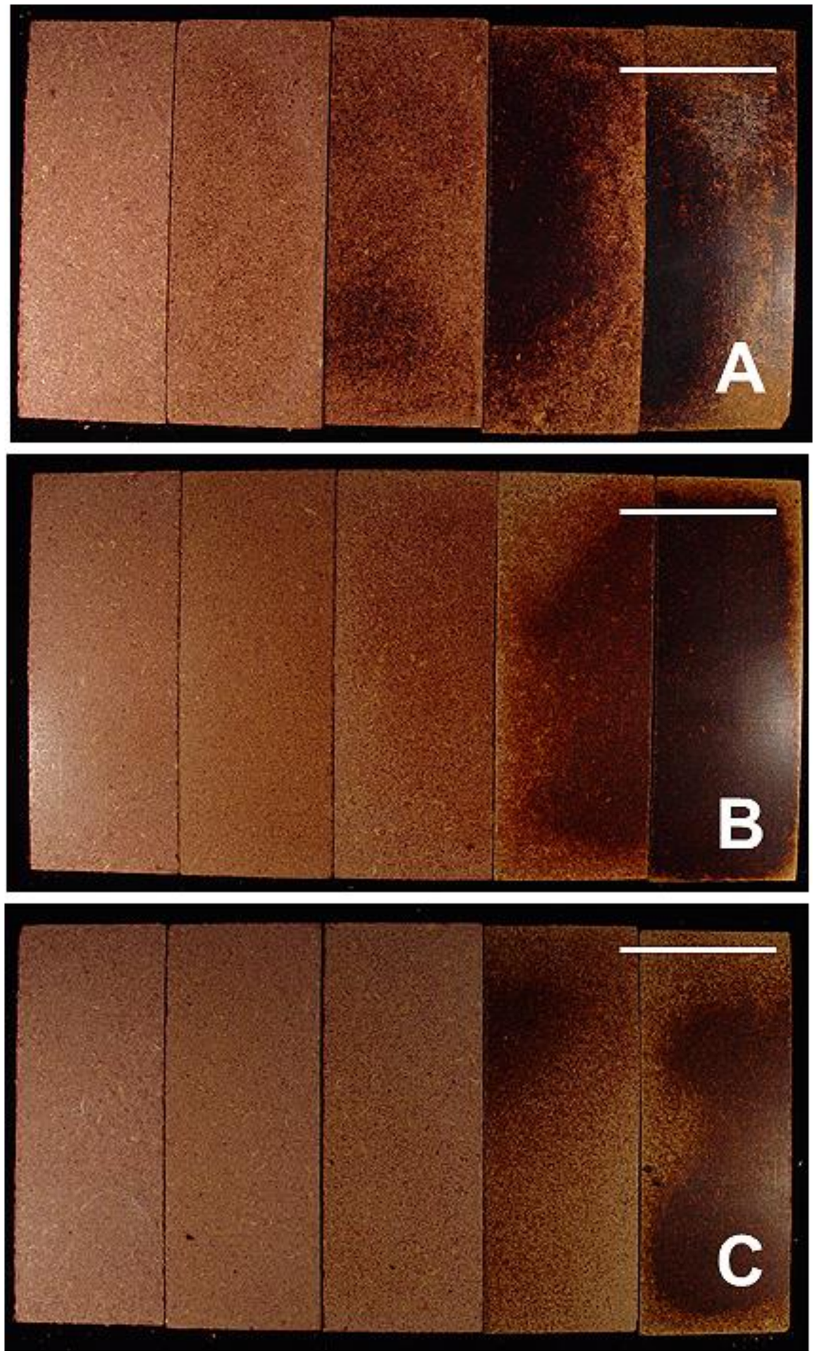

Fig. 1. Fabricated bio-composite panels. From top to bottom, (A) 10DDGS-90ERC, 15DDGS-85ERC, 25DDGS-75ERC, 50DDGS-50ERC, and 25DDGS-ERC (B) 10OOSM-90ERC, 15OOSM-85ERC, 25OOSM-75ERC, 50OOSM-50ERC, and 25OOSM-ERC (C) 10PRO-90ERC, 15PRO-85ERC, 25PRO-75ERC, 50PRO-50ERC, and 25PRO-ERC. Scale bar = 50 mm.

The original ingredients and mixture of ingredients had color properties that were considerably different from the molded CWPs (Figs. 1 to 3; Tables 6 and 7). This can be attributed to the heating and pressure employed to generate the molded panels. Other investigators reported that heat treated wood similarly exhibited color alterations, which resulted in decreases in *L**, *a**, *b**, and *C*ab* values (Zanuncio *et al.* 2015). Heating causes the destruction or alteration of extractives within wood, which causes color changes (Zanuncio *et al.* 2015). In this study, the matrices concentrations contributed to color changes of the molded bio-composite panels. As shown in Table 6 and Fig. 3, the *L** coordinates decreased 4% to 7% in the molded CWPs containing 15% matrix and 85% ERC wood *versus* the unheated original ingredients. The *L** coordinates decreased 31% to 63% in the molded CWPs containing 50% matrix and 50% ERC wood *versus* the unheated original ingredients. The other color coordinates values also showed these same trends based on the matrix ingredient concentrations employed (Fig. 3).

Fig. 2. Ingredients and mixtures prior to molding that were employed in the fabrication of CWPs. From left to right: top row: ERC (≤600 μm particles), DDGS, 15DDGS-85ERC and 50DDGS-50ERC; middle row: ERC (600-1700 μm particles), 00SM, 15OOSM-85ERC and 50OOSM-50ERC; bottom row: ERC (≤600 and 600-1700 μm particles) PRO, 15PRO-85ERC and 50PRO-50ERC. Scale bar = 50 mm.

Table 6. Color Analysis of CWPs Compared to Original Ingredients [a]

Description[b]	*L**	*a**	*b**	*C**ab	*H**
	value	value	value	value	Value
ERC (≥600 µm)*	47.8 ± 0.04a	15.9 ± 0.03a	13.1 ± 0.01a	20.5 ± 0.03a	0.7 ± 0.01a
ERC (600-1700 µm)*	42.8 ± 0.55a	16.2 ± 0.01a	11.1 ± 0.25b	19.7 ± 0.08b	0.6 ± 0.01a
ERC (≥1700 um)*	44.0 ± 0.45a	16.3 ± 0.09a	12.1 ± 0.01c	20.1 ± 0.01a	0.6 ± 0.01a
DDGS*	60.8 ± 0.03b	3.5 ± 0.01b	18.4 ± 0.01d	18.7 ± 0.01b	1.4 ± 0.01b
OOSM*	75.5 ± 0.1c	2.1 ± 0.01c	9.6 ± 0.1e	9.8 ± 0.01c	1.4 ± 0.01b
PRO*	93.5 ± 0.09d	-1.5 ± 0.01d	10.5 ± 0.03f	10.6 ± 0.03d	-1.4 ± 0.01c
50DDGS-50ERC*	46.9 ± 0.15a	12.3 ± 0.05e	12.9 ± 0.02	17.8 ± 0.03e	0.8 ± 0.01d
15DDGS-85ERC*	53.3 ± 0.04e	6.8 ± 0.01f	16.4 ± 0.01	17.7 ± 0.01e	1.2 ± 0.01b
15OOSM-85 ERC*	53.9 ± 0.10e	10.6 ± 0.01g	10 ± 0.1f	14.6 ± 0.01f	0.8 ± 0.01d
50OOSM-50 ERC*	66.1 ± 0.01f	4.8 ± 0.01h	10.2 ± 0.1f	11.3 ± 0.01g	1.1 ± 0.01b
15DDGS/PRO-85ERC*	51.4 ± 0.02e	12.4 ± 0.01e	12.0 ± 0c	17.2 ± 0.01e	0.8 ± 0.01d
50DDGS/PRO-50ERC*	64.1± 0.01f	5.1 ± 0.01h	13.6 ± 0.01a	14.5 ± 0.01f	1.2 ± 0.01b
10DDGS-90ERC	47.1 ± 0.51a	13.3 ± 0.14	11.4 ± 0.25b	17.5 ± 0.21e	0.7 ± 0.01a
15DDGS-85ERC	45.2 ± 1.17a	12.5 ± 0.76e	11.0 ± 0.53b	16.7 ± 0.97e	0.7 ± 0.02a
25DDGS-75ERC	43.0 ± 2.0a	12.3 ± 0.39e	12.0 ± 0.69c	17.2 ± 0.73e	0.8 ± 0.03d
50DDGS-50ERC	27.0 ± 1.86g	7.1 ± 1.00j	6.7 ± 1.2ge	9.8 ± 1.71c	0.7 ± 0.03a
75DDGS-25ERC	24.4 ± 1.48g	4.6 ± 1.04h	5.5 ± 1.2g	7.2 ± 1.69g	0.9 ± 0.03d
10OOSM-90ERC	50.9 ± 0.54e	11.6 ± 0.24e	11.2 ± 0.24b	16.1 ± 0.31e	0.8 ± 0.01d
15OOSM-85ERC	50.2 ± 0.43e	11.3 ± 0.19i	11.7 ± 0.26b	16.3 ± 0.28e	0.8 ± 0.01d
25OOSM-75ERC	49.3 ± 0.64e	10.3 ± 0.25g	13.2 ± 0.28a	16.8 ± 0.22e	0.9 ± 0.02d
50OOSM-50ERC	34.8 ± 2.96h	9.5 ± 0.36g	11.8 ± 0.94b	15.2 ± 0.88f	0.9 ± 0.04d
OOSM-ERC 75-25	25.5 ± 1.25g	7.1 ± 0.39j	8.2 ± 0.76e	10.9 ± 0.91g	0.9 ± 0.02d
10PRO-85ERC	47.5 ± 0.89e	13.0 ± 0.22e	12.2 ± 0.25	17.8 ± 0.11e	0.8 ± 0.02d
15PRO-85ERC	47.6 ± 1.35e	12.13 ± 0.19e	13.0 ± 0.15a	17.8 ± 0.13e	0.8 ± 0.02d
25PRO-75ERC	36.5 ± 2.81h	12.3 ± 0.41e	11.9 ± 0.87b	17.1 ± 0.91e	0.8 ± 0.03d
50PRO-50ERC	24.9 ± 0.72g	8.7 ± 0.48g	7.3 ± 0.45e	11.4 ± 0.71g	0.7 ± 0.01a
75PRO-25ERC	23.4 ± 1.8g	6.5 ± 0.44f	5.3 ± 0.41g	8.34 ± 0.65	0.7 ± 0.01a
15DDGS/PRO-85ERC	48.5 ± 0.7e	12.5 ± 0.10e	13.5 ± 0.2a	18.3 ± 0.2	0.8 ± 0.02a
50DDGS/PRO-50ERC	23.5 ± 0.7g	7.6 ± 0.70j	6.3 ± 0.6ge	9.8 ± 1	0.7 ± 0.01a
15DDGS/PRO-85ERC/HEX	49.4 ± 0.5e	12.6 ± 0.20e	14.2 ± 0.2h	19 ± 0.1	0.8 ± 0.01a
50DDGS/PRO-50ERC/HEX	23.5 ± 0.8g	7.6 ± 0.70j	5.9 ± 0.7g	9.6 ± 1.1	0.7 ± 0.02a
15DDGS/PRO-85ERC/ST	54.2 ± 0.3e	11.5 ± 0.01i	15.2 ± 0.1g	19.1 ± 0.1	0.9 ± 0.03d
50DDGS/PRO-50ERC/ST	31.2 ± 1.3i	10.8 ± 0.4g	11.4 ± 0.7b	15.7 ± 0.8	0.8 ± 0.01a

[a] Means and standard errors (n=5) within a column with different letters are significantly different ($p \leq 0.05$).; [b] Description asterisks indicates original ingredients and mixed unmolded ingredients.

Table 7. Pearson Correlation Coefficient Values for Matrix and Wood Concentrations and Color Properties for All ERC CWPs[a]

Correlations:	Matrix (%)	Wood (%)	*L** value	*a** value	*b** value	C^*_{ab} value	*H** value
Matrix	--	-1.000*	-0.917*	-0.922*	-0.806*	-0.887*	-0.117
Wood	-1.000*	--	0.917*	0.922*	0.806*	0.887*	0.117
*L**	-0.917*	0.917*	--	0.850*	0.899*	0.908*	0.432
*a**	-0.922*	0.922*	0.850*	--	0.865*	0.957*	0.123
*b**	-0.806*	0.806*	0.899*	0.865*	--	0.974*	0.583
C^*_{ab}	-0.887*	0.887*	0.908*	0.957*	0.974*	--	0.393
*H**	-0.117	0.117	0.432	0.123	0.583	0.393	--

[a] Values with asterisks were significant at p = 0.05.

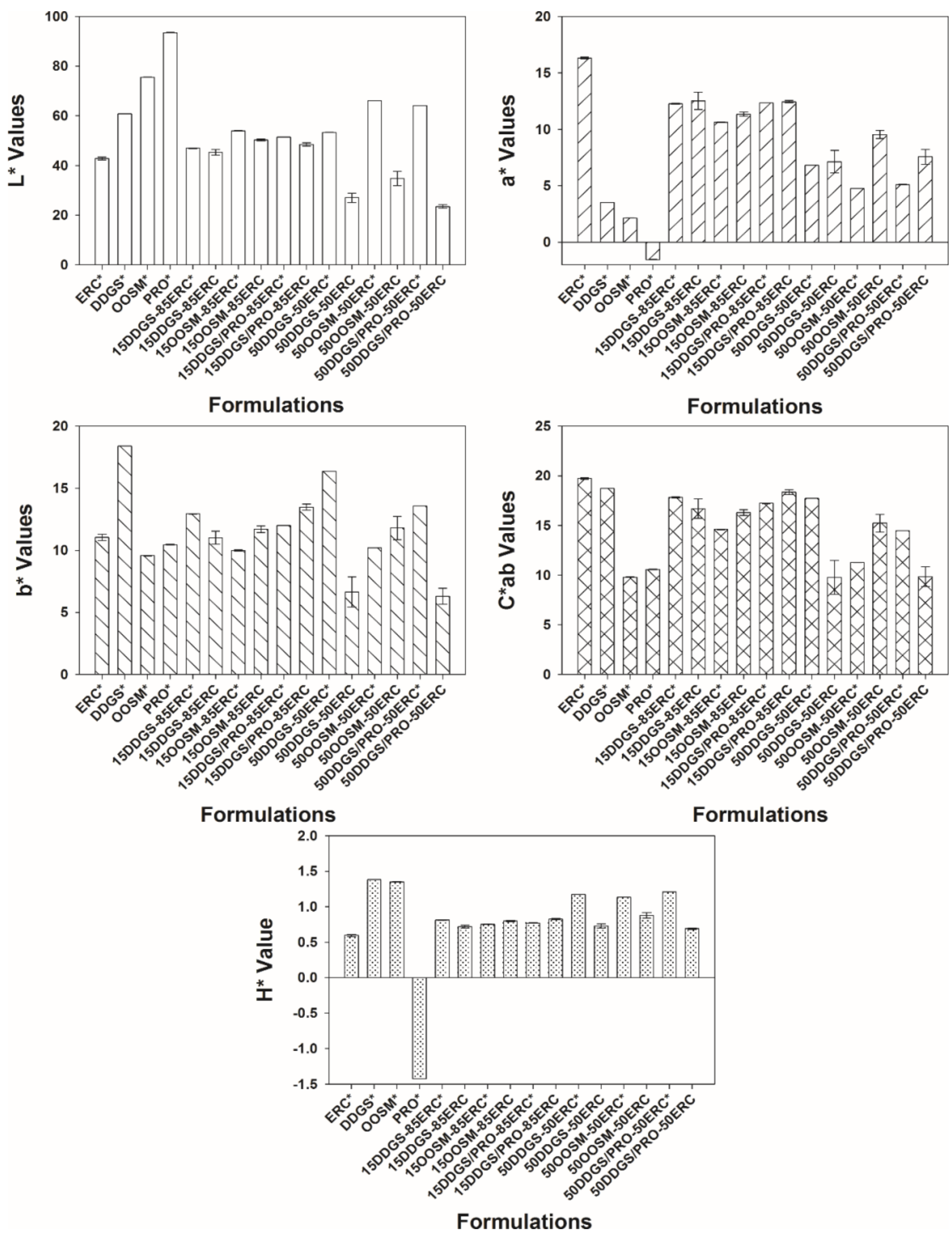

Fig. 3. Comparison of the color properties of ingredients and the molded CWPs. Asterisk signifies unmolded ingredients.

Termite Responses

Weight loss, termite mortality, and moisture gain percentages are provided in Fig. 4. Southern pine (SP) control wafers exhibited the least resistance to termites, incurring a 16% termite mortality while complete mortality (100%) was recorded in all but one of the bio-composite panel treatments. Southern pine samples exhibited the least moisture gains compared to CWPs. This can be attributed to the greater structural integrity of the solid wood wafers compared to CWPs. However, SP exhibited the highest percentage of weight loss compared to the CWPs. Eastern redcedar is well documented to be a termiticidal due to the presence of CWO, which is a natural toxin (Kard *et al.* 2007; Tumen *et al.* 2013; Eller *et al.* 2018). Eastern Redcedar particleboard-flakeboard panels prepared with 7% UF exhibited up to 95% termite mortality (Kard *et al.* 2007). Similarly, 100% termite mortality was recorded in five of the six CWPs. There was a high significant Pearson coefficient correlation between the termite mortality and the weight loss (0.945). Oddly, the 15DDGS-85ERC panels caused the least termite mortality (41%) of all the bio-composite panels tested. This may be attributed to the poorer binding ability of the DDGS compared to the two-other bio-adhesives (OOSM and PRO). Higher weight losses occurred for 15DDGS-85ERC compared to the other tested CWPs. Likewise, 15DDGS-85ERC also exhibited somewhat lower MOR, MOE, WA, and TS values compared to CWPs utilizing OOSM or PRO matrices (Table 2). This suggests that flexural properties could be related to the dimensional stability and to termite resistance properties. Interestingly, even when 50% of the bio-composite was employed as the bio-adhesive matrix, complete termite mortality was achieved. Apparently, the use of bio-adhesive matrices did not interfere with the termite resistance of the ERC wood. CWPs containing 50% bio-adhesives and 50% ERC were as effective in exhibiting termite resistance and preventing weight loss as CWPs containing 15% bio-adhesives and 85% ERC. Distiller's dried grain with solubles, OOSM, and SBM flours may have termiticidal properties in their own right due the presence of their extractives. Acda and Cabangon (2013) reported that PB composed of tobacco stalk and wood particles exhibited termiticidal properties and attributed this to the alkaloid nicotine naturally occurring in tobacco.

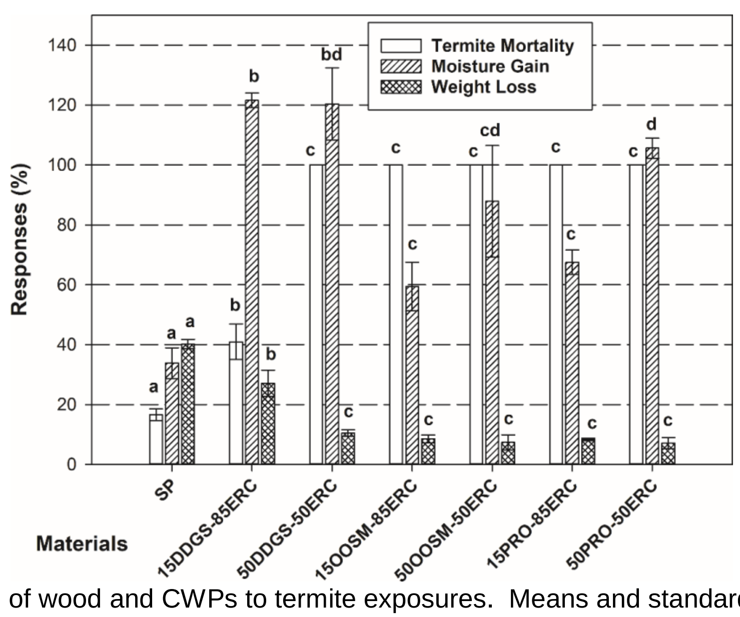

Fig. 4. Response of wood and CWPs to termite exposures. Means and standard errors are provided; treatment responses with different letters were significantly different ($p \leq 0.05$).

CONCLUSIONS

1. Composite wood panels (CWPs) from distiller's dried grains with solubles and eastern redcedar (DDGS-ERC), Osage orange seed meal and eastern redcedar (OOSM-ERC), and defatted commercial soybean meal flour-Prolia with eastern redcedar (PRO-ERC) were fabricated containing 10% to 75% matrices along with 90% to 25% ERC wood. Distiller's dried grain with solubles, OOSM or PRO flours reacted with ERC particles varying from ≥1700 μm to produce panels that satisfied the nominal flexural properties required by the European Committee for Standards.
2. The dimensional stability values (*i.e.*, TS and WA) of CWPs dramatically improved when matrices of 50% or 75% were employed. The nominal TS properties of commercial CWPs required by the European Committee for Standards were satisfied by several bio-composite formulations.
3. The surface roughness properties of the CWPs were found to be closely related their composition. Significant Pearson coefficient correlations were found comparing the physical, flexural, dimensional stability, and surface roughness properties.
4. Matrices prepared with equal portions of DDGS and PRO (*i.e.*, 15% DDGS/PRO-85% ERC) produced CWPs that exhibited higher flexural properties than using DDGS alone (*i.e.*, 15DDGS-85ERC) but lower flexural properties than PRO alone (*i.e.*, 15PRO-85ERC).
5. Composite wood panels fabricated from solvent-extracted ERC wood (*i.e.*, 15DDGS/PRO-85RC/HEX or MEOH) with their CWO removed were found to exhibit inferior flexural and dimensional stability properties compared to CWPs fabricated with unextracted ERC wood (*i.e.*, 15DDGS/PRO-85ERC). However, when the proportion of the matrix was increased to 50%, no differences in these properties were detected.
6. The color properties of the mold CWPs were considerably affected by the concentration of the matrices and wood employed.
7. Composite wood panels can exhibit high termite resistance.

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