Surface Characteristics of Particleboard Produced from Hydro-thermally Treated Wheat Stalks

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Surface characteristics were studied for particleboards produced from hydro-thermally treated (HTT) and non-treated (NT) wheat stalk (WS). Wood and wheat stalk particles were used as experimental materials. The wheat stalk particles were subjected to HTT at a temperature of 180 °C for 8 minutes in a steam explosion machine. HTT and NT WS particles were added at 10%, 20%, 30%, and 40% to the wood particles. The surface roughness and wettability of the produced panels were determined. The roughness measurements, average roughness (R_a), maximum roughness (R_{max}), and mean peak-to-valley height (R_z) were performed using a fine stylus tracing technique. The wetting behavior of the panels was characterized by the contact angle method (goniometer technique). The contact angle (CA) measurements were obtained by using a KSV Cam-101 Scientific Instrument connected with a digital camera and computer system. Statistical analyses showed significant differences in the surface roughness and wettability of the particleboards following hydro-thermal modification. The addition of WS to the panels significantly decreased the roughness values. However, all of the HTT groups exhibited higher roughness compared to NT groups. The CA values decreased when the WS content increased. The wettability of the particleboard containing HTT WS particles was improved.

Keywords: Hydro-thermal treatment; Particleboard; Wheat stalks; Surface roughness; Wettability

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INTRODUCTION

In Turkey, approximately 27 million tons of wheat stalk (WS) is produced annually. The WS is morphologically more complicated than wood. It contains a relatively large number of elements, including the actual fibers, parenchyma cells, vessel elements, and epidermal cells, which contain a high amount of ash and silica. The epidermal cells of the WS are the outermost surface cells that are covered by a thin wax layer. This layer deteriorates the moisture absorbance of WS's from water-based adhesives (Markessini *et al*. 1997; Hafezi and Hosseini 2014). The chemical composition of the WS is similar to wood; however, it has lower cellulose and higher hemicellulose and lignin quantities compared to wood (Markessini *et al.* 1997).

There are many research studies on the utilization of annual plants in the production of wood-based panels, such as particleboard and fiberboard (Turreda 1983; Yalınkılıç *et al*. 1998; Grigoriou *et al*. 2000; Nemli *et al*. 2001; Bektaş *et al*. 2002; Nemli *et al*. 2003; Mo *et al*. 2003; Güler and Özen 2004; Alma *et al*. 2005; Bektaş *et al*. 2005; Güler *et al*. 2006; Cöpür *et al*. 2007; Güler *et al*. 2008). Most studies reported that mechanical properties of the panels met the standard values while their physical properties (thickness swelling (TS) and water absorption (WA)) could not meet the standard value (Nemli *et al*. 2001; Bektaş *et al*. 2002; Nemli *et al*. 2003; Mo *et al*. 2003; Güler and Özen 2004; Alma *et al*. 2005; Bektaş *et al*. 2005; Güler *et al*. 2006; Cöpür *et al*. 2007; Güler *et al*. 2008). One of the most successful ways to increase water resistance of the wood and wood-based composites is thermal modification. Property changes of thermally-treated wood mainly depend on the modification of hemicelluloses, which contribute to the sorption of water. Dehydration due to reduction of free hydroxyl groups leads to decreased moisture uptake; an addition contribution to the decrease is the formation of hydrophobic substances due to cross-linkage reactions of the wood polymers (Tjeerdsma and Militz 2005). The thermal treatment also affects the surface properties of wood and wood composites (Petrissans *et al.* 2003; Sernek *et al.* 2004; Follrich *et al.* 2006; Gerardin *et al.* 2007; Ayrılmış and Winandy 2009; Jarusombuti *et al.* 2010).

Many attempts have been made to improve the properties of wood composites *via* application of different treatments. Bekhta *et al*. (2013) evaluated some properties of particleboards manufactured from WS that were pretreated with acetic anhydride, soapy solution, hot water, and steam. They concluded that the pretreatment of WS improved physical and mechanical properties of particleboards. Bekhta *et al.* (2018) investigated the addition of ethanol to urea formaldehyde (UF) adhesive and boiling in soapy solution to improve the bonding quality of the wood-WS composites. The hydro-thermal treatment (HTT) can be alternative way to increase the bondability of wood and WS particles with UF resin removing the thin wax layer of the WS. The objectives of this study were to investigate the surface roughness and wettability of particleboards produced from hydro-thermally treated WS's and to increase the use of annual plants in the production of wood based panels.

EXPERIMENTAL

Materials

Industrial wood particles (pine and beech) and the WS were used as experimental materials in this study. The industrial wood particles were supplied from a commercial particleboard plant in Kocaeli/Turkey, and WS's were harvested from Duzce in the Black Sea region of Turkey. The WS's were chipped and classified for core layer (CL) and surface layer (SL) particles. The particles that remained in the ranges 3 to 1.5 mm and 1.5 to 0.8 mm, as separated by sieves, were utilized in the CL and SL of the particleboards, respectively. The particles were dried at 100 °C temperature in a technical oven to reach target 3% moisture content. The HTT was applied to WS particles in a steam explosion machine at 180 °C temperature for 8 min (Fig. 1).

The particleboards were produced under laboratory conditions (Fig. 2). The target density was 600 kg.m^{-3}. The panels were design to consist of 35% particles at the SL and 65% at the CL. The control group contained 100% industrial wood particles. The HTT and non-treated (NT) WS particles were added from 10% to 40% to the particleboards.

The UF resin at 55% solid content and 1.25 formaldehyde/urea mole ratio was used at 8% for CL and 10% for SL based on the oven dry weight of particles. One-percent ammonium chloride (concentration 20%) solution was added to the UF resin as a hardener based on the solid adhesive amount. The CL and SL particles were separately placed in a drum blender and sprayed with UF resin and hardener for 8 min to obtain homogenized mixture. The particleboards were pressed in a hot press using a pressure of 2.6 MPa and a temperature of 150 °C for 7 min. The panels were conditioned in a climate chamber for three weeks before the tests. The experimental design is shown in Table 1.

Fig. 1. HHT application to the WS particles in the steam explosion machine

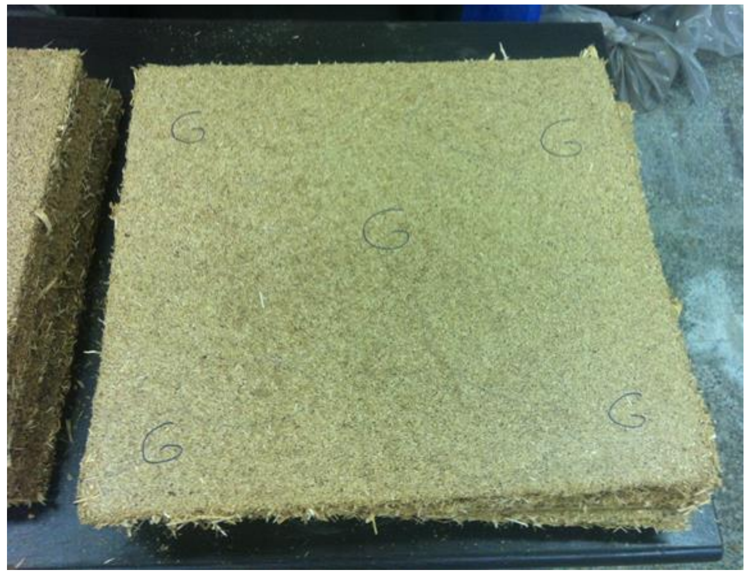

Fig. 2. The particleboards produced from HTT and NT WS-wood particles

Table 1. Experimental Design

Board Type	Method	Temperature (°C)	Time (min)	Wheat Stalk Ratio (%)	Wood Particle Ratio (%)
Control	Non-treated	-	-	0	100
HTT-10	Hydro-thermally treated	180	8	10	90
HTT-20				20	80
HTT-30				30	70
HTT-40				40	60
NT-10	Non-treated	-	-	10	90
NT-20				20	80
NT-30				30	70
NT-40				40	60

Methods

Determination of surface roughness

Twenty samples with a size of 50 mm x 50 mm were cut from each type panel for the surface roughness (SR) measurements. All samples were conditioned in a climate chamber with a relative humidity of 65% and temperature of 20 °C until they attained 12 % equilibrium moisture content prior to measurements. The measurement points were randomly marked on the sample surfaces, and the measurements were accomplished with a Mitutoyo SJ-301 surface roughness tester (Fig. 3). In this study, average roughness (R_a), mean peak-to-valley height (R_z), and maximum roughness (R_{max}) were used to evaluate the SR characterization according to ISO 4287 (1997) standard.

Fig. 3. The surface roughness measurement of the particleboards

Determination of wettability

The contact angle (CA) method was used to evaluate the wettability of the produced panels. The SR measurement samples were also used for the CA measurements. The CA values were obtained by using sessile drop method with an imaging system (KSV Cam-101 Instrument, Finland). The image was captured immediately after the droplet of distilled water was placed on the surface, and then every 1 second for the duration 60 seconds.

Data analyses and statistical methods

For the surface roughness and wettability, all multiple comparisons were first subjected to an analysis of variance (ANOVA) at $p<0.01$. Significant differences between mean values of the panel groups were determined using Duncan's multiple range test.

RESULTS AND DISCUSSION

Table 2 lists some statistical parameters of the average roughness (R_a) and Duncan's multiple range test results of the produced particleboards.

Table 2. Average Roughness and Duncan's Test Results of the Produced Panels

Property	Panel Type	*N*	*X* (µm)	SD	SE	X_{min} (µm)	X_{max} (µm)	C_v (%)
R_a (µm)	Control	40	21.1 A	4.7	0.8	12.3	33.1	22.5
	HTT-10	40	21.1 A	4.7	0.7	12.7	30.7	22.2
	HTT-20	40	18.5 BC	5.1	0.8	9.5	35.7	27.4
	HTT-30	40	19.8 AB	4.2	0.7	9.8	28.7	21.0
	HTT-40	40	17.1 CD	5.5	0.9	7.2	28.6	32.0
	NT-10	40	20.3 AB	4.1	0.6	11.7	30.7	20.1
	NT-20	40	15.9 D	3.9	0.6	8.2	23.5	24.4
	NT-30	40	15.3 D	4.1	0.6	7.6	26.4	26.7
	NT-40	39	16.0 D	3.6	0.6	8.9	25.0	22.5

N: number of specimens, *X*: average, SD: standard deviation, SE: standard error, X_{min}: minimum value, X_{max}: maximum value, C_v: coefficient of variation. Groups with identical capital letters in a column indicate that there is no statistical difference ($p < 0.05$) between the samples according to Duncan's multiple range test.

The control group made from 100% wood particles had the highest average roughness value of 21.1 µm, while the lowest average roughness (15.3 µm) was observed for the particleboards containing 30% NT WS particle in the mixture. Büyüksarı *et al.* (2010) determined that the R_a value of particleboards produced from 100% wood particles was 9.77 µm. The differences could be arise from raw material characteristics, species, particle size, shelling ratio, manufacturing variables, press parameters, resin content, and sanding process of the particleboards (Hiziroglu *et al.* 2008). The addition of WS to the particleboards significantly improved the average roughness values. This can clearly be observed by inspection of raw data from SR profilometer that recorded noticeably shallower ridges and valleys compared to control panels (Fig. 4). Similar improvements were also observed by Hafezi and Hosseini (2014). They found that the particleboards produced from 100% WS particles had the smoothest surface compared to particleboards containing poplar particles in the 0% silane level. Nemli *et al.* (2005) stated that raw material type and characteristics affected the surface roughness of particleboards. The improvement of the surface roughness of the produced particleboards was most likely because of the morphological properties of wood and WS. The WS is morphologically more complicated than wood. It contains a relatively large number of elements, including the actual fibers, parenchyma cells, vessel elements, and epidermal cells, which contain a high amount of ash and silica (Markessini *et al.* 1997; Hafezi and Hosseini 2014). Also, the WS has lower cellulose and higher hemicellulose and lignin quantities compared to wood (Markessini *et al.* 1997).

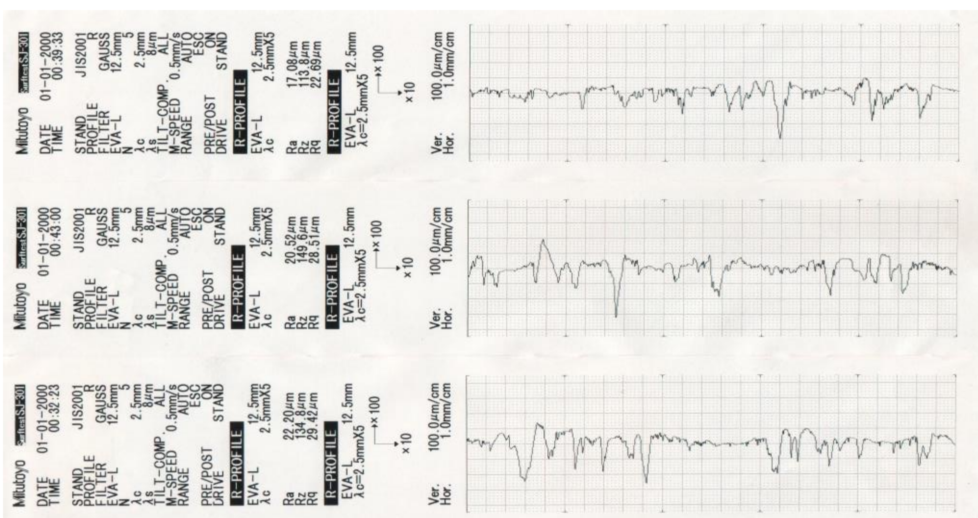

Fig. 4. Typical surface roughness profiles of some produced particleboards. NT-30 (Upper), HTT-30 (Middle), and control (bottom)

All of the HTT groups exhibited higher average roughness values compared to NT groups (Fig. 5). However, this difference was not significant for the groups containing 10% HTT and NT WS particles. Candan *et al.* (2012) concluded that the thermal modification process significantly affected the surface roughness values of the plywood panels. It was reported that the surface roughness of the plywood panels improved with increasing thermal treatment temperature up to 170 °C but the roughness value increased as modification temperature increased to 190 °C. Yasar *et al.* (2020) observed a continuous decrease in the surface roughness value of the particleboards produced from 100% pine particles due to the increase of the heat treatment temperature from 120 °C to 180 °C. In another study, Jarusombuti *et al.* (2010) determined that the MDF panels produced from thermally treated rubberwood fibers had smoother surface than that of NT fibers. They found that the MDF panels treated at 180 °C for 30 min had the smoothest surface with an R_a value of 4.02 µm, while the roughest surface was observed for the MDF panels containing 100% NT rubberwood fibers with an R_a value of 6.93 µm.

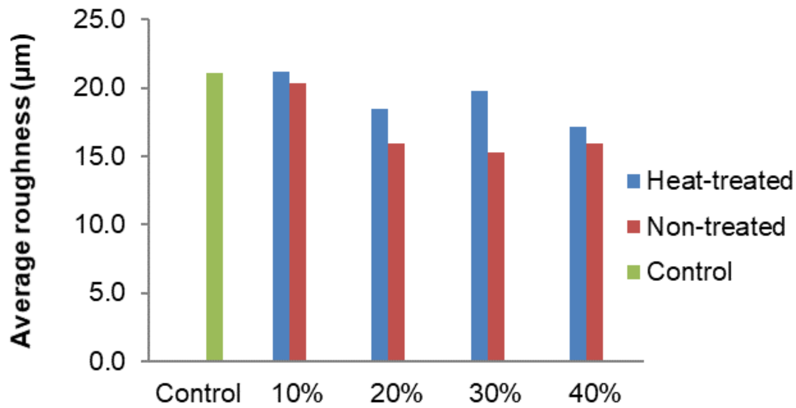

Fig. 5. The average roughness values of the particleboards produced from HTT and NT WS particles

In the NT panels, the average roughness value of the panels decreased with increasing WS content in the panels (Fig. 5). The NT-10 (containing 10% WS) had the highest roughness value, while the NT-30 (containing 30% WS) had the smoothest surface. The NT-30 exhibited 27.5% and 24.6% lower average roughness value compared to the control and NT-10 groups, respectively. Şahin *et al.* (2018) determined that all surface roughness parameters were decreased due to the increase of the use of rice husks in the particleboard. Güler (2019) concluded that the surface roughness values decreased with increasing of canola particles ratio in the particleboards. It was found that the R_a values were 15.10 µm and 5.11 µm for the particleboards produced from 100% pine particles and 100% canola particles, respectively. On the contrary, Büyüksarı *et al.* (2010) found that the increase in pine cone ratio up to 50% in the particleboard resulted in higher R_a value. The particleboards containing 50% pine cone had 58.7% higher R_a value compared to control group. These decreases and increases in the average roughness values of the current study and previous studies can be attributed to differences in morphological and chemical characteristics of the WS, rice husk, canola, and pine cone. In the HTT panels, similar to the NT panels, the panel surfaces became smoother as the WS content increased. HTT-10 had the roughest surface with the value of 21.1 µm and HTT-40 had the smoothest surface. The HTT-40 had 19.0% lower roughness value than those of the control and HTT-10 groups.

Table 3 lists some statistical parameters of the maximum roughness (R_{max}) and Duncan's multiple range test results of the produced particleboards.

Similar trends were found for the maximum roughness values. The addition of WS to the panels significantly affected the R_{max} values. Büyüksarı *et al.* (2010) determined that the R_{max} value of particleboards produced from 100% wood particles was 52.77 µm. All of the HTT groups had greater maximum roughness compared to NT groups. This difference was statistically significant for the groups containing 30% and 40% WS particles. The NT-

30 showed a 17.0% lower maximum roughness value compared to NT-10. In the HTT panels, the maximum roughness was found to be the highest in the HTT-30 group, while HTT-40 had the lowest value. The HTT-40 had 7.6% and 6.7% lower maximum roughness value compared to HTT-30 and HTT-10, respectively. Jarusombuti *et al.* (2010) showed that the MDF panels produced from thermally treated rubberwood fibers had lower R_{max} values compared to control group. They found that the R_{max} value of the control and treated at 180 °C for 30 min were 52.08 µm and 38.56 µm, respectively.

Table 3. Maximum Roughness and Duncan's Test Results of the Produced Panels

Property	Panel Type	*N*	*X* (µm)	SD	SE	X_{min} (µm)	X_{max} (µm)	C_v (%)
R_{max} (µm)	Control	40	177.5 A	31.9	5.0	104.0	261.9	18.0
	HTT-10	40	180.0 A	30.5	4.8	121.1	249.7	17.0
	HTT-20	40	167.5 AB	29.2	4.6	107.8	262.7	17.4
	HTT-30	40	181.8 A	33.2	5.2	117.0	249.4	18.2
	HTT-40	40	167.9 AB	34.9	5.5	80.2	231.7	20.8
	NT-10	40	176.2 A	37.0	5.8	97.4	242.3	21.0
	NT-20	40	158.1 BC	32.7	5.2	86.6	237.1	20.7
	NT-30	40	146.2 C	27.7	4.4	94.4	219.3	19.0
	NT-40	39	146.3 C	34.5	5.5	41.7	219.1	23.6

N: number of specimens, *X*: average, SD: standard deviation, SE: standard error, X_{min}: minimum value, X_{max}: maximum value, C_v: coefficient of variation. Groups with identical capital letters in a column indicate that there is no statistical difference ($p < 0.05$) between the samples according to Duncan's multiple range test.

The mean peak-to-valley height (R_z) values and Duncan's multiple range test results of the produced particleboards are shown in Table 4.

Table 4. Mean Peak-to-valley Height and Duncan's Test Results of the Produced Panels

Property	Panel Type	*N*	*X* (µm)	SD	SE	X_{min} (µm)	X_{max} (µm)	C_v (%)
R_z (µm)	Control	40	132.7 A	23.1	3.6	88.4	183.9	17.4
	HTT-10	40	133.6 A	21.8	3.4	95.7	194.6	16.3
	HTT-20	40	123.0 AB	25.9	4.1	78.6	216.5	21.0
	HTT-30	40	129.0 A	24.4	3.9	65.7	182.6	18.9
	HTT-40	40	115.1 BC	26.7	4.2	56.7	178.6	23.2
	NT-10	40	129.5 A	21.1	3.3	84.1	167.8	16.3
	NT-20	40	107.7 CD	18.8	3.0	70.2	143.5	17.5
	NT-30	40	102.1 D	18.9	3.0	60.9	148.2	18.5
	NT-40	39	106.3 CD	23.7	3.8	23.5	142.2	22.3

N: number of specimens, *X*: average, SD: standard deviation, SE: standard error, X_{min}: minimum value, X_{max}: maximum value, C_v: coefficient of variation. Groups with identical capital letters in a column indicate that there is no statistical difference ($p < 0.05$) between the samples according to Duncan's multiple range test.

The control group had a higher R_z value compared to the groups containing WS particles except for HTT-10. The addition of WS to the panels significantly improved the

R_z values of the produced panels. Similar results were found by Hafezi and Hosseini (2014) for WS and by Şahin *et al.* (2018) for rice husk particleboards. Şahin *et al.* (2018) determined that the R_z values were 21.18 µm and 15.78 µm for the particleboards produced from 100% wood particles and containing 30% rice husk particles, respectively. On the contrary, it was found that the increase in pine cone ratio up to 50% in the particleboard resulted in higher R_z value (Büyüksarı *et al.* 2010). They stated that the R_z values were 36.22 µm and 60.96 µm for the particleboards produced from 100% wood particles and containing 50% pine cone particles, respectively. In the NT panels, the R_z value of the panels decreased with increasing WS content in the panels. The NT-10 had the highest R_z, a value of 129.5 µm, while the NT-30 had the lowest R_z at 102.1 µm. The NT-30 exhibited an R_z value 21.2% lower than NT-10.

All of the HTT groups had higher R_z values compared to NT groups containing a similar percent of WS particles. However, this difference was not significant for the groups containing 10% and 40% WS. In the HTT panels, similar to the NT panels, the R_z value of the panels decreased as the WS content increased. HTT-10 had the highest R_z value and HTT-40 had the lowest R_z value. The HTT-40 exhibited a 13.8% lower R_z value compared to HTT-10. Jarusombuti *et al.* (2010) showed that the MDF panels produced from thermally treated rubberwood fibers had significantly lower R_z values compared to control group. It was found that the R_z value of the control and treated at 180 °C for 30 min were 41.15 µm and 28.06 µm, respectively.

Figure 6 indicates the CA values of the produced panels. The effect of HTT on the wettability of the panels was significant.

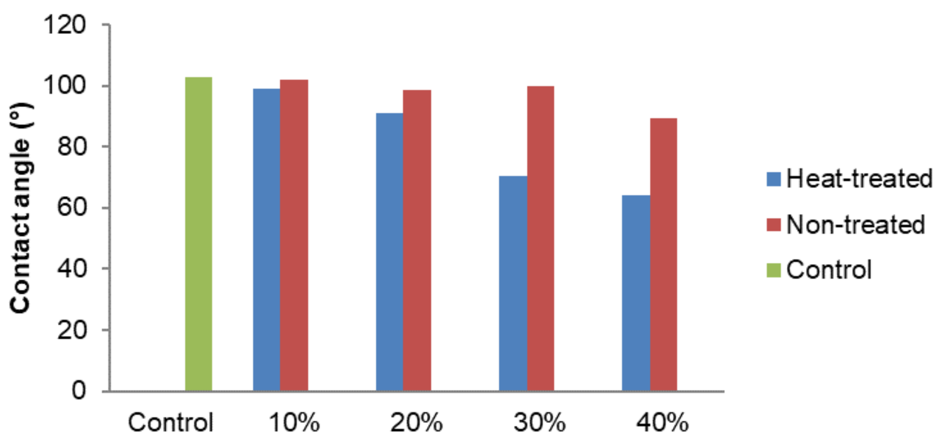

Fig. 6. CA values of the particleboards produced from HTT and NT WS particles

The control group had the highest CA value (102.7°), while the group containing 40% HTT WS particles had the lowest value (64.2°). The addition of WS to the panels significantly affected the CA values. Similar results were found by Hafezi and Hosseini (2014). They determined that the CA was reduced when the WS content in the panels increased; the exception to this was for the group containing 100% WS particles. Wettability is crucial for good adhesion in bonding between particleboard and coating. When the CA is zero, perfect wetting of a surface occurs. Baharoglu *et al.* (2011) stated that liquids wet surfaces when the CA is less than 90°. The wettability of the particleboard containing HTT WS particles was improved. Although the heat treatment worsened the wettability of wood and wood-based panels (Petrissans *et al.* 2003; Sernek *et al*. 2004; Follrich *et al.* 2006; Gerardin *et al*. 2007), HTT improved the wettability of the panels containing WS particles. This may be due to the removal of the silica, non-polar extractives, and thin wax layer of the epidermal cell by the HTT application. In a cross-section of the WS, the epidermal cells are the outermost surface cells and are covered by a thin waxy layer. This wax layer deteriorates the moisture absorbance of straw from water-based adhesives such as urea–formaldehyde (UF) resin (Markessini *et al.* 1997; Yasin *et al*. 2010; Hafezi and Hosseini 2014). Han *et al.* (2010) reported that steam explosion treatment of straw improved acidity and wettability and decreased silica content. Han *et al.* (1998) stated that the wettability was improved by ethanol/benzene treatment due to removal of the wax-like substance and non-polar extractives of the WS surfaces. Bekhta *et al*. (2018) concluded that the bonding quality of the particleboard containing WS particles could be improved by boiling.

CONCLUSIONS

1. The addition of wheat stalk (WS) particles decreased the surface roughness (SR) values and increased the water-wettability of the panels. Wettability and surface roughness of particleboard are very important when the panels are to be coated with thin overlays. The particleboards containing WS particles can be utilized for coated panels application due to improved SR and wettability.
2. Hydro-thermal treatment (HTT) and WS ratio had a statistically significant effect on the SR values and wettability of the panels.
3. The application of HTT to WS particles increased the water-wettability of the panels, however, SR values of the panels became higher.
4. The SR and contact angle (CA) values decreased when the WS ratio increased.

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