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Hydrothermal treatment of *Populusdeltoides* wood: Analyses of colour and chemical changes through FT-NIR

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ABSTRACT

Wood modification aims to enhance wood colour, dimensional stability, durability and other properties. Hydro-thermal method is an important method of wood modification. The objective of this work is to evaluate colour and chemical changes in wood due to hydro thermal treatments and to evaluate potential of near infrared spectroscopy to predict these properties for quality control. Populusdeltoides, a plantation grown timber with dull, pale-whitish colour, was taken for hydrothermal treatment at four temperatures (125 °C, 150 °C, 175 °C and 200 °C) and two durations 20 min and 40 min. Near infrared spectra and colour coordinates were collected from radial and tangential faces of treated wood. Proportion of lignin and holo-cellulose were determined. Results reveal that colour properties of wood changed significantly. Mean lightness (L) value in control was 72.42±6.25, whereas, treatments 125 °C (20 min to 200 °C (40 min) resulted lightness values 63.57±3.89 to 32.5±1.99.Mean red/ green (a*) increased with the temperature upto 175 °C then decreased, mean value of a* for control was 6.4±1.81, whereas, treatments 125 °C (20 min) to 200 °C (40 min) yielded a* values 6.82±0.67 to 8.42±1.04.Color coordinate value b* decreased with the temperature. Mean value of b* for control was 24.54±3.08, whereas, treatments 125 °C (20 min) to 200 °C (40 min) resulted b* values 22.3±0.56 to 11.33±2.9.Colour saturation and hue angle decreased significantly with temperature increase during hydrothermal treatment. Proportion of holo-cellulose decreased while that of lignin increased. Partial least square (PLS) NIRS spectroscopic models were developed and used to predict various wood properties. Results suggest that NIRS can be used to predict colour, chemical composition of hydro-thermally treated wood.*

Key words: *hydro-thermal treatment, near infrared spectroscopy, wood colour*

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I. Introduction

Wood is a naturally available versatile material with superior mechanical, aesthetics, acoustic, thermal properties than its other counterparts. Being a ligno-cellulosic and hygroscopic material, not only it is prone to attack by biological agents like fungus, borers but also dimensionally unstable due to desorption-adsorption of water. Preservative impregnation and chemical modification are established techniques to protect wood from biological agents and achieve dimensional stability to prevent financial losses. Thermal modification of wood has attracted attention of researchers around the globe as a mean to impart durability and dimensional stability in the wood without use of any chemicals. In the heat treatment, wood is subjected to high temperature (up-to 260 °C) to bring chemical changes in wood to achieve desired objectives. Due to thermal treatment, changes in chemical composition of wood, properties like density, color, strength have been reported in last two decades.

Reduction in wood hygroscopicity induced by high temperature was reported as early as in 1915 (Tiemann, 2015). Moreover, degradation in wood due to heating in presence of water occurs many times faster than that of dry wood (Skaar, 1976). In particular, wood modification through hydrothermal treatment is found to be of more interest as it causes characteristic modification in wood chemical composition. Result of these changes is improvement in colour and aesthetics as wood gains darker tone due to thermal treatment (Unsal et al., 2003).

Moreover, improvement and homogenisation of colour and other properties of wood may enhance marketability of thermally modified wood. Since, colour changes in heat treatment is significant, matching the colour and other properties becomes important in mass production of thermally modified woods. Near-Infrared Spectroscopy (NIRS) has been widely used by the researchers for quantification and predictive modelling of wood properties. NIRS has been identified as a potential tool for screening and quality control in thermal modification process.Schwanninger et al. (2011) presented a comprehensive review of NIR band assignment. Sandberg et al. (2013) recommend need of the investigations on chemical changes and process optimisation to develop effective and workable methods of wood modification.

Populusdeltoides is widely grown in northern India by farmers to cater the wood needs of panel industries. Colour of the wood is pale white and is not preferred by solid wood based industries due to its dull aesthetics. Present work aims to study the effect of hydrothermal treatment on colour, chemical content of*Populusdeltoides* wood and using NIRS for predictive modelling for quality control.

II. Materials and Methods

Sample Preparation: -Four logs of recently felled, eight-year-old two trees of *Populusdeltoides*, with log girth approximately 90 cm and length 550 cm, were flat sawn into 50.8 mm thicknesses. Samples of 50.8mm (thick) × 50.8mm (wide) × 152.4mm (length) along the grain were prepared for hydrothermal treatment. The samples were prepared from sound and seasoned wood. Before cutting the samples of desired size, the planks were planed on both sides in order to get an even surface. A total of 160 samples were produced for the test. The trial included a total of eight treatments. There are ten replications of each treatment. For each treatment, there were 10 control specimens.

*Hydro-thermal treatment:*The prepared samples were soaked in water for three days before the hydro-thermal treatment to ensure that the cell walls of the wood specimens were saturated with water. The samples were removed out of the water and placed in autoclaves in batches of 10 for each treatment as given in table 1.

Table 1: Details of hydro-thermal treatment

		Temperature							
	Control	**125 ºC**		**150 ºC**		**175 ºC**		**200 ºC**	
Treatment duration (minutes)	--	20	40	20	40	20	40	20	40
No. of test specimens	10	10	10	10	10	10	10	10	10

After the treatments, the specimens were taken out of the autoclave and kiln dried till the moisture content of the specimens came down to moisture content range of 10-12%.

Near infrared spectroscopy: Spectra were recorded using the FT-NIR spectrophotometer (Brucker, MPA). 4000 cm^{-1} to 12820 cm^{-1} (780-2400 nm) was its wavelength range. The diffuse reflectance mode (resolution: 8 cm^{-1}) is how the device functions. The fiber optic module with the TE-InGaAs (internal, NEP 2 9 101 10-13 WHZ-1/2) detector configuration was used to take the spectra of solid wood samples. For every spectrum, 32 scans were gathered. Four spectra from radial and tangential faces—that is, eight spectra per specimen on a wood sample—were averaged to create the single average spectrum for the sample.

Color measurement

Colormeasurement was done on the control and hydrothermal treated and dried wood specimens of poplar using Color Meter (X-rite colorimeter, Model Ci 4100). All color measurements were conducted under typical illumination condition of D65 with Specular Component Included (SCI). Lightness (L*), yellowness (a*) and redness (b*) color coordinates were evaluated by performing four measurements in the middle tangential face of each specimen.

Chemical changes

The chemical constituents of the control and treated wood specimens were determined following the standard methods outlined in the TAPPI test method T257 (Anonymous, 1993).

Development of calibration model

OPUS 6.5 software was used multivariate analysis and the development of the NIR spectrum based calibration model. Out of 10 hydrothermally treated specimens, 7 specimens' spectra was used for the development of calibration model. For the development of calibration model for L*, a*, b*, saturation, the spectra were transformed with Savizky-Golay Transform, IInd derivative (17smoothening points). For the pre-processing of the spectra for hue angle, lignin and holo-cellulose, standard Normal Variate (SNV) transformation was carried out. Multivariate analysis was carried out using partial least square (PLS) regression analysis method to obtain the regression model along with its indicators (R^2, RMSECV).

Testing of the model

Out of total 10 hydrothermally treated specimens, 3 specimens were used for testing of the predictive power of the developed calibration model using the spectra of the corresponding specimens.

III. Results and Discussion

Spectral distribution of hydrothermally treated and control wooden specimens

Figure 1 shows the Near-Infrared (NIR) spectra of wooden specimens subjected to hydrothermal treatment at various temperatures (125°C, 150°C, 175°C, and 200°C) and durations (20 min and 40 min), along with a control sample. The x-axis represents the wavenumber (cm⁻¹), while the y-axis indicates the absorbance. The spectra reveal changes in the chemical composition of wood due to thermal modification. At higher treatment temperatures and longer durations, noticeable shifts and intensity variations in the absorption bands are observed, particularly in the regions associated with hydroxyl (-OH), carbonyl (C=O), and aromatic vibrations, indicating degradation of hemicelluloses, modification of lignin, and reduction in hydroxyl groups.

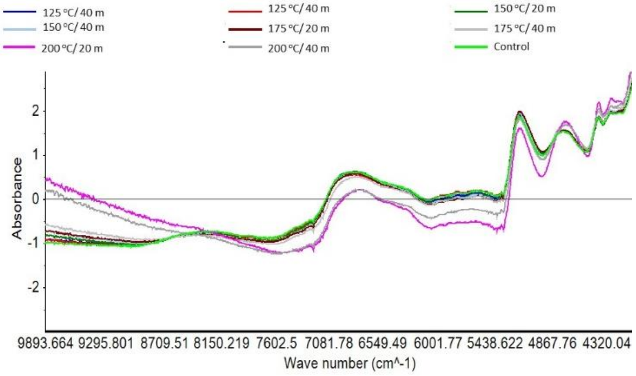


Figure 1: Spectral distribution of treated and control specimens

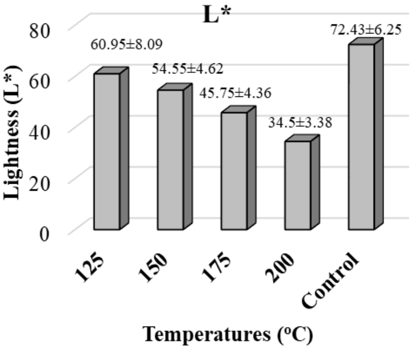
Compared to the control, the spectra of treated specimens show reduced absorbance in the high wavenumber region and altered peaks in the mid and lower regions, suggesting significant changes in moisture content and chemical structure. The most pronounced differences are seen at 200°C for 40 minutes, where the absorbance dips and peaks deviate markedly from the control, reflecting more extensive thermal degradation. These spectral changes confirm that hydrothermal treatment alters the wood's chemical and physical characteristics, which can influence its durability, dimensional stability, and hygroscopic behavior.

In the NIR spectra of the hydrothermally treated wood specimens, characteristic absorbance regions can be associated with specific wood components and functional groups. The broad region around 7000–5200 cm⁻¹ corresponds mainly to overtone and combination bands of hydroxyl (-OH) stretching vibrations, which are abundant in cellulose and hemicelluloses and reflect wood's hygroscopic nature (Schwanninger et al., 2011). A reduction in absorbance in this region after treatment suggests a decrease in hydroxyl groups, consistent with thermal degradation of hemicellulose and reduced moisture affinity.

Another important region is around 5200–4000 cm⁻¹, where combination bands of C–H, C=O, and aromatic C=C vibrations appear, representing lignin and carbonyl-containing degradation products. Specifically, the peaks near 4700–4300 cm⁻¹ are often attributed to aromatic C–H and C–O overtones from lignin, while the bands near 5800–5400 cm⁻¹ include contributions from both hydroxyl and carbonyl groups(Schwanninger et al., 2011). Changes in these regions with increasing temperature and time indicate chemical modifications in lignin and cellulose structure, such as condensation of lignin and loss of acetyl/carbonyl groups from hemicelluloses.

Lightness (L*)

Fig. 2 and 3 present changes in lightness (L*) of the treated specimens along with controls. Fig. 2&3 reveal that significant changes occurred in lightness of the specimens and there was a gradual decrease in lightness on increasing the severity of the treatments with the respect to temperature and duration.



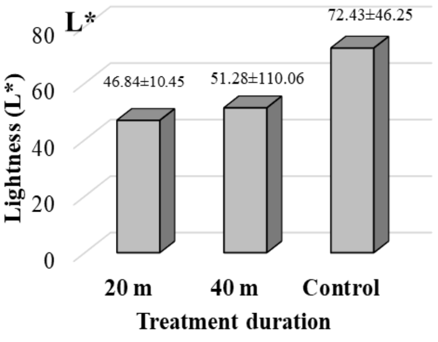


Figure 2: Lightness (L*) value of hydrothermally treated wooden specimens at different temperatures

Figure 3: Lightness (L*) value of hydrothermally treated wooden specimens at time durations

Mean L* value in control was 72.42±6.25, whereas, treatments 125 ºC (20 min), 125 ºC (40 min), 150 ºC (20 min), 150 ºC (40 min) 175 ºC (20 min) 175 ºC (40 min), 200 ºC (20 min) and 200 ºC (40 min) yielded lightness values 63.57±3.89, 58.32±10.38, 55.34±5.84, 53.75±3.09, 48.41±3.44, 43.1±3.56, 36.49±3.36, 32.5±1.99 respectively. Two way Analyses of variance (ANOVA) indicates that there is a significant difference between two time-duration (20 min and 40 min) with respect to change in lightness (df=01, alpha=0.05, p=0.001). Mean lightness value for 20 min treatment duration was 50.95 and for 40 min, it was 46.92, whereas, for control samples it was 72.42. Tukey HSD post hoc test put 20 min, 40 min and control specimen's lightness values in three separate groups. Similarly, two way Analyses of variance (ANOVA) indicates that there is a significant difference among four temperatures (df=3, alpha=0.05, p=<0.001). Mean lightness value for 125 ºC, 150 ºC, 175 ºC and 200 ºC were 60.94, 54.55, 45.75 and 34.49. Thus, there is a general trend in decrease in lightness on increase in temperature. Lengowski et al. (2018) also reported similar trends on thermal modification of *Eucalyptus grandis* and *Pinustaeda*. However, as compared with treatment duration, drop in lightness was more pronounced due to temperature increase. In similar studies on *Pinusnigra*wood, Guller (2012) concluded that temperature had greater influence than time on colour of wood.

Tukey HSD post hoc test put 125 ºC, 150 ºC, 175 ºC, 200 ºC and control specimen's lightness values in five separate groups. ANOVA for interaction between time and temperature indicated that there was no interaction between time and temperature (df=3, alpha=0.05, p=0.654). This means that, time and temperature worked independently on lightness reduction. Yao et al. (2012) reported that during heat treatment, formation of condensation products, phenolic substances with low molecular weight and oxidation in lignin result in increased light absorption in visible region, resulting in decrease in lightness value. Yao et al. (2012) further confirmed decrease in hydroxyl groups and release of acid and quinoid and carboxylic groups occur during heat treatment.Srinivas and Pandey (2012) also have reported decrease in lightness in similar work.

Red/ green (a*)

Fig 4 presents chromatic color coordinates a*of the wooden specimens along with the controls. Fig 4 and 5reveal that there was a gradual increase in a* (from green towards red color) from temperature 125 ºC to 175 ºC, thereafter, there was a slight dip in increase (towards green) from 175 ºC to 200 ºC. In natural wood, increase in poly-phenols are mainly responsible for an increase in a* (Gierlinger et al., 2004).

In similar studies on firwood, Kucerova et al. (2016) revealed that between 200 ºC to 220 ºC, red component of the color reached its maximum value (towards red), and further increase in temperature resulted change towards greener color. Srinivas and Pandey (2012) have also reported an increase in a* colour coordinate initially, then, decrease.

Moreover, in general, higher is the value of a* from going 20 min treatment duration to 40 min. Value of a* in control wood in lower as compared with the treated wood specimens.

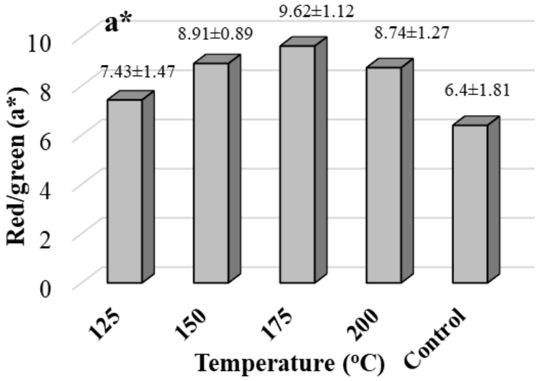


Figure 4: Red/green (a*) value of hydrothermally treated wooden specimens at different temperatures

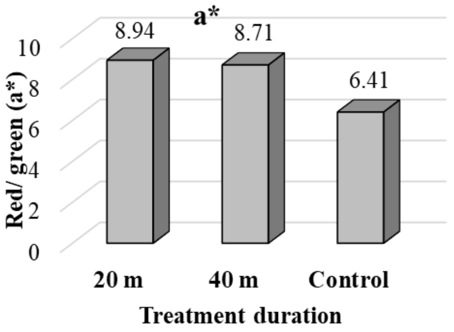


Figure 5: Red/green (a*) value of hydrothermally treated wooden specimens at time durations

Mean value of a* for control was 6.4±1.81, whereas, treatments 125 ºC (20 min), 125 ºC (40 min), 150 ºC (20 min), 150 ºC (40 min) 175 ºC (20 min) 175 ºC (40 min), 200 ºC (20 min) and 200 ºC (40 min) yielded a* values 6.82±0.67, 8.02±1.81, 8.49±0.94, 9.34±0.64, 9.1±0.89, 10.14±1.13, 9.06±1.44, 8.42±1.04 respectively. Two-way ANOVA analyses reveals that both time (df=1, alpha=0.05, p=0.033) and temperatures (df=3, alpha=0.05, p=<0.001) had significant impact of a* chromatic color coordinate. However, as in L*, the interaction between time and temperature of the treatments was found to be non-significant with respect to a* (df=3, alph=0.05, p=0.08).

Post hoc analyses using Tukey HSD test revealed that a* values of control and 125 ºC / 20 min specimens belonged to same group and 125 ºC / 40 min was placed in separate group from them. Rest of the treatments were placed in one group. This means that a* value of control and 125 ºC specimens were significantly different from rest of the treatments (which were similar with each other. Relatively lower value of a* as in 200 ºC is significantly not different from 150 ºC, 175 ºC treatments. Tuckey HSD post hoc test reveals that although time had significant effect on a* and as compared with the control, significantly higher a* were found between treated woods, there was no significant difference between both the time duration viz. 20 min (8.37), 40 min (8.98). However, effect of temperature was significantand a* values due to 150 ºC (8.7), 175 ºC (8.9) and 200 ºC (9.6) were significantly higher than control and 125 ºC and were placed in same group (150ºC, 175 ºC and 200 ºC).

Natural color of poplar wood is pale whitish, and the results suggest that a significant shift in color coordinates towards red can be achieved using hydrothermal treatments.

Yellow/ blue (b*)

Fig. 6 and 7present values of chromatic color coordinates. It may be seen that as compared with the control specimens, value of b* is decreasing from yellowness to blueness. Similar trends were observed by Lengowski et al. (2018), however, Srinivas and Pandey (2012) reported that b* first increase but later decreases.Fig. 6 reveal that effect of temperature on decrease in value of b* is notable. However, a very small dip in value of b* is observed when the treatment time was increased from 20 min to 40 min.

Mean value of b* for control was 24.54±3.08, whereas, treatments 125 ºC (20 min), 125 ºC (40 min), 150 ºC (20 min), 150 ºC (40 min) 175 ºC (20 min) 175 ºC (40 min), 200 ºC (20 min) and 200 ºC (40 min) yielded b* values 22.3±0.56, 23.41±1.91, 21.59±1.76, 22.28±1.74, 19.56±1.31, 18.8±1.96,15.83±2.06, 11.33±2.9respectively. Two-way ANOVA of b* reveals that b* didn't change significantly by increasing time duration from 20 min to 40 min (df=1, alpha=0.05, p=0.07). Guller (2012) has also reported that temperature has greater effect on properties of thermally treated wood as compared with duration. Lee et al. (2018) attributed color change to production of chromophores due to degradation of hemicellulose.

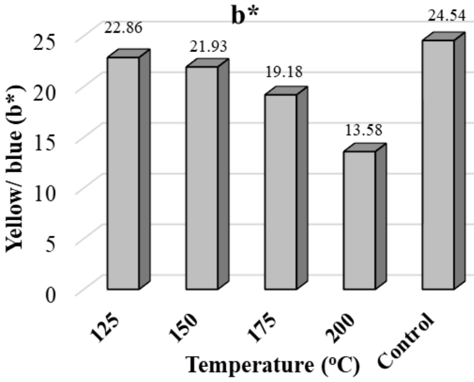


Figure 6: Red/green (a*) value of hydrothermally treated wooden specimens at different temperatures

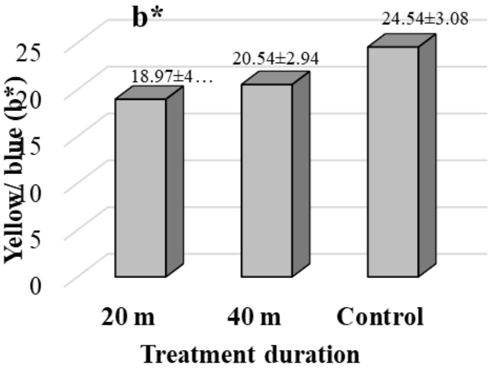


Figure 7: Red/green (a*) value of hydrothermally treated wooden specimens at time durations

However, temperature had a significant impact on reduction of b* values (df=3, alpha=0.05, p=<0.001). Moreover, unlike L* and a*, interaction effect between temperature and time duration was found to be significant (df=3, alpha=0.05, p=<0.001). Tukey HSD post hoc test placed all the b* value due to various temperatures in separate groups.

Colour Saturation and Hue angle

Fig. 8 present colour saturation and hue angle of the treated specimens. Colour saturation depends upon variations in a* and b*. Hue angle is expressed in degrees of angle as chromatic axis rotates counter-clock wise. Hue angle 0º represents red color, similarly, 90º, 180º and 270º are yellow, green and blue colours respectively. From fig. 9 it can be seen that changes in color saturation are not affected significantly due to increase in time from 20 min (21.61) to 40 min (21.11) at 0.05 significance level.

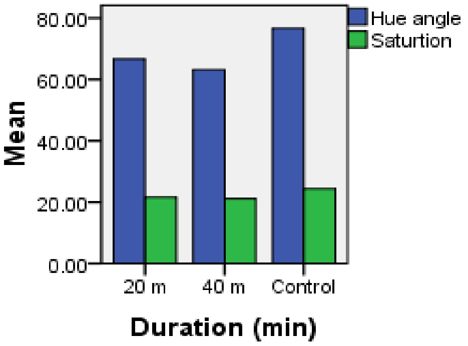


Figure 8: Hue angle and saturation value of hydrothermally treated wooden specimens at different temperatures

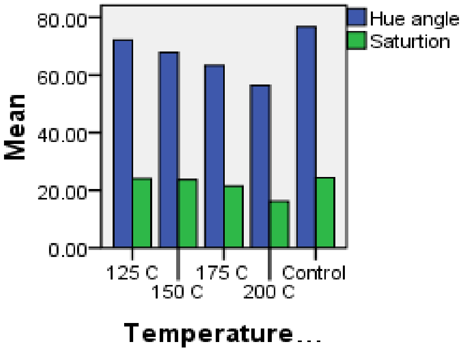


Figure 9: Hue angle and saturation value of hydrothermally treated wooden specimens at different temperatures

However, there is a significant change in hue angle due to time duration of the treatment (df=1, alpha=0.05, p=<0.001). Hue angle for control samples is 76.72, for 20 min duration of the treatment is 63.44 and for 40 min, 66.6. Thus, there is a marked decrease in hue angle due to increase in treatment time. Lengowski et al. (2018) also reported decrease in hue angle after heat treatment.

Tukey HSD post hoc test places saturation levels of 200 ºC temperature in a separate group with mean value (least) of 16.22 and that of 175 ºC in another separate group (21.48). However, saturation levels of control, 125 ºC and 150 ºC temperature treatments are same and placed in same group.

Hue angles are found to be placed in separate groups for control (76.5), 20 min (66.6) and 40 min (40 min). Similarly, hue angles due to different temperature treatments are placed in separate groups by Tukey HSD post hic test at 0.05% significance level viz. control (76.72), 125 ºC (72.11), 150 ºC (68.11), 175 ºC (63.82), 200 ºC (57.19).

Lignin and holo-cellulose

Fig. 10 presents similarity index with control specimens through OPUS 6.5 after analyses of NIR absorption spectra. It reveals that chemical changes in wood are gradual from 125 ºC to 175 ºC. However, a drastic change occurred at temperature 200 ºC at both the time duration. Similarity index ranged from 40-50% at 200 ºC, whereas, it was in range of 85 to 97% for less severe treatments. Poly-condensation reaction and crosslinking with the cell wall result in structural changes in lignin (Ali et al., 2021). Main component in holo-cellulose reduction may be due to significant reduction in hemicellulose due to thermal degradation (Hillis and Rozsa, 1985). Yin et al. (2011) reported effect of hydrothermal treatment (180 ºC) on spruce wood using FT-IR spectroscopy. They found that degradation of gluco-mannan along with loss of C=O group occurred in aromatic lignin skeleton.

Fig. 11 presents values of lignin and holo-cellose content of treated and control specimens. Lignin and holo-cellulose content in control specimens was 28.83% and 70.88% respectively. However, from fig. 10 it may be seen that as severity of the treatments is increased, proportion of holo-cellulose is decreasing and that of lignin is increasing.

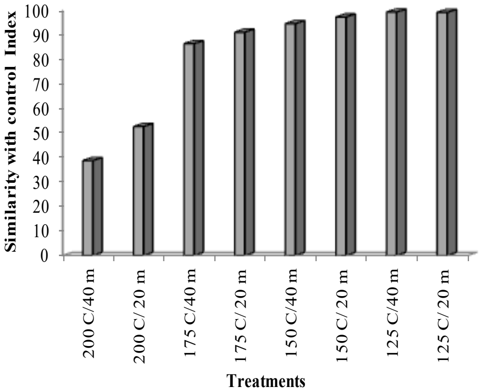


Figure 10: Spectroscopic similarity Index with control specimens

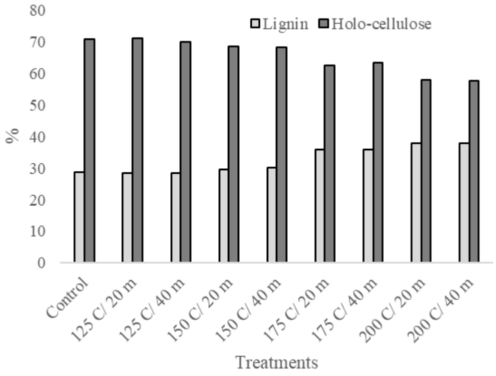


Figure 11: Lignin and holo-cellulose content in control and hydrothermally treated specimens

It shows that 200 ºC temperature treatment for both the time durations is least similar as compared with that of other treatments. The steeper fall in similarity at 200 ºC as compared with the steepness of lignin and holo-cellulose indicate that apart from changes in lignin and hemicellulose, other constituents might have changed drastically at 200 ºC. ANOVA test reveals that changes in lignin are not significant due to increase in time duration of the treatments from 20 min to 40 min (df=1, alpha=0.05, p=0.471). However, the changes due to temperatures are significant (df=3, alpha=0.05, p=<0.001). Moreover, there is no significant interactions between time and temperature with respect to lignin content changes. Tukey HSD test puts lignin content of control and 125 ºC in one group, 150 ºC in second group and that of 175 ºC and 200 ºC treatments in another group.

For holo-cellulose content also, time durations (20 m and 40 m) don't affect significantly on changes in holo-cellulose content ((df=1, alpha=0.05, p=0.139). However, temperature has significant impact on holo-cellulose contents (df=3, alpha=0.05, p=<0.001). Similar to the pattern found with lignin, 200 ºC and 175 ºC temperature affected significantly on changes in holo-cellulose content and were placed in separate groups using Tukey HSD post hoc test.

NIRS models and predictive diagnostics

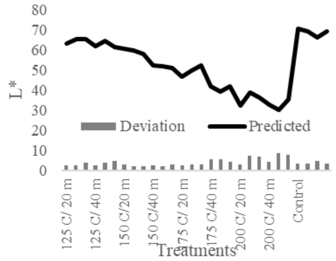
Table 2 presents summary of predictive models developed using NIRS using PLS multivariate analyses tool. For all the color coordinates (L*, a* and b*) and saturation model development, transformation was used using Savizky-Golay Transformation, IInd derivative. For rest of the variables (hue angle, lignin, holo-cellulose) SNV Transformation was used.

Table 2: **NIRS models and their predictive diagnostics for various wood properties studied**

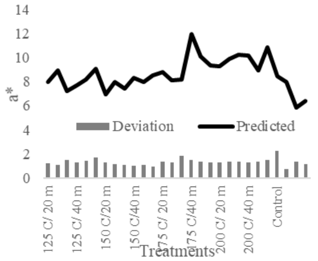
Sl. No.	**Property**	**Transformation**	**Factors**	**R^2 (C)**	**R^2 (P)**	**Slope (C)**	**Slop (P)**	**Offset (C)**	**Offset (P)**	**RMSEC**	**RMSEP**
1	L*	SG	5	0.92	0.84	0.92	0.85	4.1	7.7	3.7	5.34
2	a*	SG	5	0.69	0.42	0.69	0.49	2.6	4.3	0.99	1.38
3	b*	SG	3	0.79	0.74	0.79	0.75	4.23	5.12	0.79	0.74
4	Saturation	SG	3	0.78	0.74	0.78	0.74	4.95	5.69	0.78	0.74
5	Hue angle	SNV	3	0.82	0.79	0.82	0.80	12.15	13.54	0.82	0.80
6	Lignin	SNV	3	0.75	0.56	0.76	064	8.04	11.5	2.4	3.32
7	Holo-cellulose	SNV	5	0.82	0.57	0.82	0.72	12.3	18.7	2.9	4.54
SG= Savizky-Golay Transformation, SNV= Standard Normal Variate Transformation, C=calibration, P=prediction											

Coefficient of regression (R^2) of the NIRS calibration models show that L* of the wood had highest R^2 of calibration and prediction, hue angle (0.82, 0.79), holo-cellulose (0.82, 0.57). Least R^2 was obtained for a* (0.69, 0.42). From RMSEC and RMSEP values, it may be seen b*, hue angle, colour saturation values can more accurately be predicted and can be used for quality control, whereas, L*, lignin, holo-cellulose can be predicted for screening purposes.

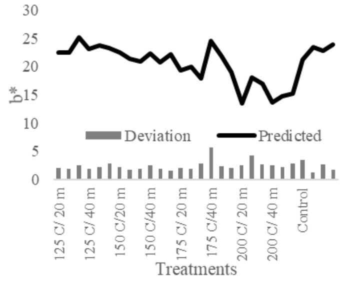
Fig. 12 (i to ix) present predicted values and deviations when FT-NIRS developed models were used to predict wood colorcharacteristics of unknown wood specimens.



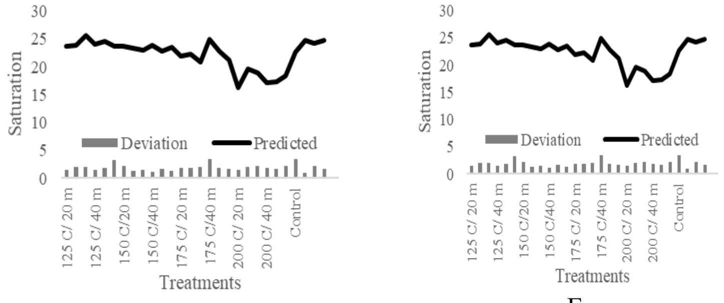
A



B



C



D

E

Fig. 12: Predictions made and deviations using NIRS- L* (A), a* (B), b* (C), Color saturation (D), hue angle (E)

As shown in fig. 12 (A-E), NIRS was able to detect correctly the trends in colour coordinates. Distinct coordinates of the control specimens were predicted with different degrees of accuracy. The deviations from actual values were also found lower.

Fig. 13 and 14 present predicted lignin and holo-cellulose content in control and treated specimens and their deviations from actual.

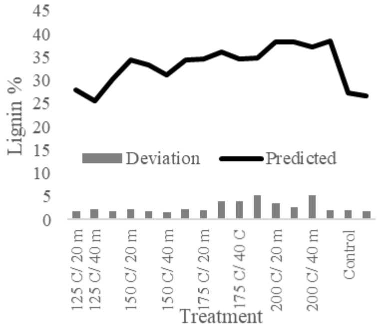


Fig. 13: Prediction of lignin content and deviation from actual

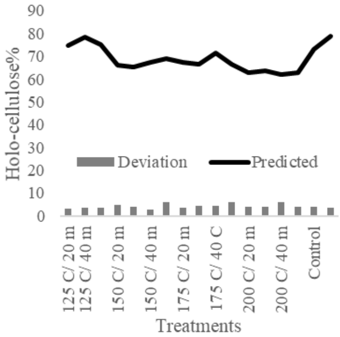


Fig. 14: Prediction of holo-cellulose content and deviation from actual

NIRS model for lignin resulted in R^2 value of 0.75 whereas for holo-cellulose it was 0.82 (SNV transformation). RMSEP of lignin and holo-cellulose were found to be 3.32 and 4.54 respectively. Wave number 5935 cm^{-1} is attributed to I^{st} overtone of C-H stretching in which C belongs to aromatic ring of lignin ((Shenk et al., 2001, Yonenobu and Tsuchikawa, 2003). Other important wave numbers are 5980, 5974, 5963, 5978 cm^{-1} which represent aromatic group in lignin ((Schwanninger et al., 2011, Sandak et al., 2011). Wave number 6874 cm^{-1} represents I^{st} overtone of phenolic groups of lignin with intermolecular H-bonding to an ether group in ortho position (Tsuchikawa et al., 2005). Other important wave numbers are 4546 cm^{-1}(Workman and Weyer, 2007), 6944 cm^{-1} (Wust and Rudzik, 1996) and 8547 cm^{-1} (Schwanninger et al., 2011) which are associated with the lignin content in wood.Wave number 4404 cm^{-1} is associated with CH_2 stretching in hemicellulose and cellulose (Tsuchikawa et al., 2005), whereas, 4780 cm^{-1} is related to OH stretching in cellulose (Bassett et al., 1963).Wust and Rudzik (1996) reported 5950 cm^{-1} as first overtone of CH stretching in hemi-cellulose.

IV. Conclusion

Hydro-thermal treatment resulted in significant decrease in lightness value in wood, treatment temperature and duration had independent effect on lightness (L*) value. An increase in a* from 125 ^{oC} to 175 ^{oC} occurs, thereafter, decrease occurs on increase in temperature. Treatment durations (20 min and 40 min) had no significant effect on a*. Hydro-thermal treatment results in decrease in value of b* is decreased and is affected mainly by treatment temperature not duration (20 min and 40 min). Colour saturation and hue angle decreases with temperature. Proportion of holo-cellulose decreased whereas, that of lignin increased. A drastic change in chemical properties at 200 ^{oC} occur. Near infrared spectroscopic partial least square models resulted in higher coefficient of regression (R^2) for L*, hue angle and holo-cellulose, whereas, satisfactory R^2 were obtained for colour saturation, a*, b* and lignin content.

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