ACTA FACULTATIS XYLOLOGIAE ZVOLEN, 67(1): 5−12, 2025
Zvolen, Technická univerzita vo Zvolene
DOI: 10.17423/afx.2025.67.1.01

COMPARATIVE COLOUR ANALYSIS OF THERMALLY MODIFIED SELECTED TEMPERATE HARDWOODS AND TROPICAL WOOD SPECIES USING PRINCIPAL COMPONENT ANALYSIS

Vidholdová Zuzana – Hýrošová Tatiana

ABSTRACT

Thermal modification is an eco-friendly and cost-effective method for enhancing the optical properties of wood by darkening its colour throughout the cross-section due to chemical changes. In this study, the colour coordinates (L^*, a^*, b^*) of thermally modified temperate hardwoods native to Central Europe were statistically compared to those of selected tropical species. The tested species – European ash, European beech, paper birch, black locust, European hornbeam, and pedunculate oak – were treated at 200°C for 3 hours. The analysis revealed that thermal modification effectively altered their colour, in some cases achieving a visual resemblance to tropical woods. Pedunculate oak and black locust closely resembled wengé, while European beech approximated the appearance of ipé. Other hardwoods only partially matched tropical tones. These findings confirm the potential of thermally modified local hardwoods to substitute tropical species in interior and furniture applications, supporting more sustainable and regionally focused utilization for biological stains.

Keywords: colour; hardwood; PCA analysis; thermal modification; tropical wood.

INTRODUCTION

Wood colour is a fundamental physical-optical property classified among macroscopic features that enable the visual differentiation of wood from various tree species. The colour arises from the presence of chromophores – specific functional groups such as carbonyl (>C=O), conjugated double bonds (-CH=CH-CH=CH-, -CH=CH-), and aromatic rings – embedded in the chemical constituents of wood, primarily lignin and low-molecular-weight extractives (e.g., pigments, tannins, resins). These chromophores selectively absorb specific wavelengths of the visible spectrum of natural daylight, thereby generating the characteristic surface colour perceived by the human visual system. In addition to interspecific variability, wood colour may also vary within a single tree as a result of heartwood formation, ageing, or environmental and processing factors. (Hon and Minemura, 2000; Babiak *et al.*, 2004; Gandelová *et al.*, 2009; Dzurenda, 2023).

The visual appearance of wood, particularly its texture and colour, plays a crucial role in determining its suitability for interior design and furniture manufacturing (Tolvaj *et al.*, 2013; Slabejová *et al.,* 2016; Dzurenda, 2022). In recent years, there has been increasing interest in modifying the colour of temperate hardwoods to achieve the dark tones typically associated with tropical species. This shift is driven not only by aesthetic considerations but also by the growing demand for environmentally responsible alternatives to tropical timber, whose harvesting often raises ecological and ethical concerns.

The color of hardwoods varies by species and is determined by the chemical composition of the wood, including cellulose, hemicelluloses, lignin, and extractive substances. While cellulose constitutes the majority of the wood cell wall and is inherently white, its colour is often masked by the hues of extractive substances, which, despite their low weight percentage, can dominate the wood's appearance. Hardwood colors range widely from light to dark shades, with longitudinal surfaces typically used for evaluation, as they are most visible on wooden objects. In contrast, cross-sections are often darker.

Temperate hardwoods without heartwood (e.g., birch, hornbeam, maple, ash, lime, and aspen) tend to be light or light brown. Denser hardwoods (e.g., oak, pear, alder, walnut, and cherry) and conifer heartwood often exhibit darker colouring due to denser fibre layers, tannins, and other extractive substances. Tropical woods, with higher extractive content, display more intense natural colour, ranging from light yellows and pinks to deep reds, purples, and blacks, as seen in ebony (Hon and Minemura, 2000). Some tropical species, such as bloodwood (*Haematoxylum campechianum* L.), are so rich in natural dyes that they are used as sources of pigments for textiles and wood. The reddish-brown heartwood of logwood yields a dark red solution, which is utilised for biological stains such as hematoxylin and haematein (Ortiz-Hidalgo and Pina-Oviedo, 2019).

A quantitative assessment of wood colour is commonly conducted using the CIELAB color space (CIE 1976), the most widely adopted system in the wood industry (Katuščák and Kučera, 2000). This system classifies temperate and tropical wood species into the positive octant, with lightness (L^*) values ranging from 20 to 90, redness ($+a^*$) from 0 to 20, and yellowness ($+b^*$) from 10 to 30 (Janin, 2001; Babiak *et al*., 2004). Compared to temperate species, tropical woods occupy a significantly broader section of the color space (da Silva *et al.,* 2017; Meints *et al.,* 2017; Vidholdová and Reinprecht, 2017).

Thermal modification is a well-established technique used to improve certain physical and aesthetic properties of wood. Conducted at elevated temperatures (typically between 160°C and 220°C) in an oxygen-deprived environment, thermal treatment leads to the degradation of hemicelluloses and the formation of chromophoric compounds, resulting in a darker and more homogeneous colour throughout the cross-section. These transformations also enhance dimensional stability and biological durability, making thermally modified wood an attractive material for indoor applications. This treatment modifies the chemical structure of hemicelluloses, cellulose, and lignin, reducing the wood's hydrophilicity and altering its properties (Hill 2007; Reinprecht and Vidholdová, 2011; Vidholdová *et al*., 2019; Hill *et al*., 2021; Sandberg *et al*., 2021). Numerous studies have explored the effects of thermal treatment on the mechanical, chemical, and optical properties of wood. However, there is limited quantitative research comparing the colour coordinates of thermally modified temperate species with those of naturally dark tropical woods. Such a comparison is essential for evaluating the potential of modified local hardwoods to serve as visual substitutes in high-end applications.

In this study, we investigate the colour changes induced by thermal modification in six temperate hardwood species native to Central Europe. Colour coordinates (L^*, a^*, b^*) were measured before and after treatment at 200°C for three hours. To assess the visual similarity between modified temperate woods and tropical references, Principal Component Analysis (PCA) was applied to the colour data. The aim of this work is to statistically evaluate the effectiveness of thermal treatment in mimicking the colour tones of selected tropical tree species and to contribute to the broader goal of sustainable, locally sourced material substitution in the wood industry.

MATERIALS AND METHODS

Wood Material

The hardwoods used in this study – European ash (*Fraxinus excelsior* L.), European beech (*Fagus sylvatica* L.), paper birch (Betula papyrifera Marsh), black locust (Robinia pseudoacacia L.), European hornbeam (*Carpinus betulus* L.), and pedunculate oak (*Quercus robur* L. – sourced from round timber felled and processed in Slovakia.Wood samples with dimensions of 150 × 15 × 300 mm were prepared by longitudinal and transverse sawing from the central part of the lumber.

The tropical wood species selected for comparison included ipé (*Handroanthus serratifolius*), iroko (*Milicia excelsa*), makoré (*Tieghemella heckelii*), sapelli (*Entandrophragma cylindricum*), and wengé (*Millettia laurentii*). These samples were obtained as naturally dried and conditioned boards, maintained at a temperature of 22 ± 2.5 °C and relative humidity of 65% in a climate chamber for 3 weeks. The boards were purchased from the trading company JAF Holz Ltd., Slovakia.

Heat Treatment Procedure

The heat treatment of native hardwoods was conducted under atmospheric pressure at a temperature of 200 ± 2.5 °C for 3 hours using a laboratory heating oven (Memmert UFB 500, Germany). The treatment was carried out at the Department of Wood Technology, Faculty of Wood Sciences and Technology, Technical University in Zvolen. The process commenced by placing the absolute dry samples in the oven at room temperature, followed by a gradual temperature increase over 45 minutes until the desired temperature was reached. The samples were maintained at this temperature for 3 hours and subsequently cooled in a desiccator under dry conditions.

Colour Measurements

Colour coordinates were measured using a Colour Reader CR-10 (Konica Minolta, Japan), which operates with a CIE 10° standard observer, CIE standard illuminant D65, and an 8 mm diameter sensor head. Prior to measurement, the samples were conditioned at a temperature of 20°C and an air relative humidity of 60%.The colour of wood was evaluated in the CIELAB colour space, specifically using the coordinates L^* (lightness), a^* (red-green axis), and b^* (yellow-blue axis).

Principal Component Analysis

A multidimensional statistical approach was employed to evaluate the data using Principal Component Analysis (PCA). In this analysis, average values were used for each condition in the time-temperature domain for the colour variables. PCA served to assess the overall structure of the data, identifying relationships and correlations between variables, as well as their relative importance. The method facilitates the detection of statistical outliers and clustering of observations. It consists in reducing the original variables to a smaller number of new (latent) variables. Latent variables were extracted in the form of orthogonal principal components (PCs), which are linear combinations of the original variables. New variables (PCs) are required to reflect as much as possible the original variables. The first component (PC1) accounts for a maximal amount of total variance in the observed variables, the second component (PC2) accounts for a maximal amount of variance in the data set that was not accounted for by the first component. PCs reflect the different effects of the original variables. Such effects can be seen from the PCA score plot, which shows the component score of the two principal components for all observed wood samples. The score plot identifies clusters of similar samples, samples outlying and strongly different from others.

Descriptive Statistics

To assess colour variation in wood samples, mean and standard deviation values for L^*, a^* and b^* were calculated. To compare the colourimetric data of selected wood samples, graphical outputs in the form of boxplot were used. The statistical analyses were processed using software Statistica 14.

RESULTS AND DISCUSSION

The colour coordinates of the native surfaces of the analysed tropical wood species and thermally modified hardwoods are summarised in Tab. 1. Among the tropical wood species, considerable variation was observed in lightness (L^*), which ranged from 34.88 for wengé, representing the darkest material in the set, to 64.50 for iroko, the lightest. This wide range illustrates the natural diversity of colouration found among tropical woods. All tropical wood species exhibited positive chromaticity values, confirming the presence of red and yellow hues in their natural appearance. Specifically, the redness coordinate (a^*) ranged from 8.00 in wengé to 16.68 in sapelli, while the yellowness coordinate (b^*) ranged from 10.34 (wengé) to 25.32 (iroko). These findings are consistent with earlier studies, including those by Meints *et al.* (2017) and da Silva *et al.* (2017), which similarly documented high variability in colour coordinates across tropical wood species. Such variability is often linked to differences in extractive content, heartwood formation, and other anatomical and chemical features that contribute to each species' distinctive optical properties. Tropical wood species are widely appreciated for their natural beauty, which is often enhanced by their rich colour tones and surface lustre. Their aesthetic attributes, in combination with favourable durability and mechanical characteristics, make them highly desirable in applications such as flooring, decorative veneers, furniture components, and high-end joinery.

Tab. 1 CIELAB colour coordinates for selected thermally treated local hardwoods and tropical woods.

Wood species	N	L^* (Lightness)		$+a^*$ (Redness)		$+b^*$ (Yellowness)	
		Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Termally modified hardwoods							
European ash	15	55.17	1.28	9.73	1.33	21.83	1.77
European beech	15	40.74	3.86	8.78	1.17	16.59	1.85
Paper birch	15	46.80	1.03	11.37	0.54	19.16	0.88
Black locust	15	34.18	1.64	7.83	1.48	9.60	1.95
European hornbeam	15	58.88	4.96	8.56	2.19	20.54	2.08
Pedunculate oak	15	35.07	1.39	7.50	0.44	9.73	0.55
Tropical woods							
Ipé	30	42.45	0.87	8.83	0.38	16.46	0.88
Iroko	30	65.70	2.14	8.32	0.85	25.87	1.61
Makoré	30	49.60	1.94	11.75	0.94	18.85	0.89
Sapelli	30	53.13	1.78	13.68	0.87	18.21	0.78
Wengé	30	35.39	1.05	8.13	0.48	10.53	1.21

In the group of thermally modified temperate hardwoods, the colour coordinates reflect the significant impact of heat treatment. The lightness (L^*) of treated samples ranged from

35.05 for black locust and pedunculate oak to 58.88 for European hornbeam. These values suggest a notable darkening effect compared to native untreated wood (not shown), a well-known outcome of thermal processing due to the degradation of hemicelluloses and the formation of coloured degradation products. Like tropical woods, all thermally modified samples also exhibited positive a^* and b^* values, indicating reddish and yellowish tones. Although these values were generally lower than in tropical wood species, their mutual similarity is noteworthy. These colour shifts are likely related to the thermal degradation of hemicelluloses and the formation of conjugated structures, contributing to the darkening and enhanced chromaticity observed in treated samples (Sandak *et al.*, 2015; Vidholdová *et al.*, 2019; Hill *et al.*, 2021; Sandberg *et al.*, 2021). The observed variation in colour response among species suggests that inherent anatomical and chemical properties, such as density and extractive content, strongly influence the efficiency of thermal treatment in achieving tropical-like hues (Janin, 2001; Babiak *et al.*, 2004; da Silva *et al.*, 2017; Meints *et al.*, 2017; Vidholdová and Reinprecht, 2017; Geffert *et al.,* 2019 and 2020).

The overlap in chromatic coordinates between some thermally treated hardwoods and certain tropical woods suggests that thermal modification can effectively mimic the appearance of exotic species. This resemblance supports the potential of using locally available hardwoods as a visual alternative to tropical timber, reducing dependency on imported materials while promoting sustainable material use. From both ecological and economic perspectives, thermally modified woods offer an attractive solution for applications that require the warm, rich tones typically associated with tropical hardwoods.

To further assess and quantify the degree of visual similarity between the studied wood species, a principal component analysis (PCA) was applied to the colourimetric data (L^*, a^*, b^*). This multivariate approach enables a more detailed exploration of patterns in colour space and facilitates the identification of species clusters based on shared optical characteristics. The results of the PCA provide a complementary statistical basis to support visual observations, revealing the extent to which thermally modified hardwoods approximate the colour profiles of tropical woods.

The results of the principal component analysis (PCA) based on the L^*, a^*, and b^* colour coordinates are shown in Fig. 1.

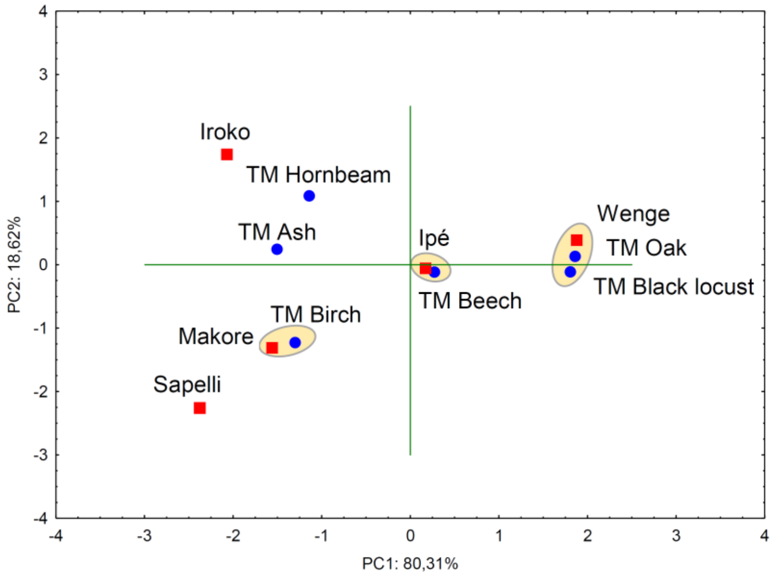

Fig. 1 PCA score plot of tropical and thermally modified wood species.

The first two principal components (PC1 and PC2) together explained 98.93% of the total variance in the dataset, with PC1 accounting for 80.31% and PC2 for 18.62%. This high level of explained variance confirms the suitability of PCA for reducing dimensionality while preserving the essential structure of the data.

The PCA score plot differentiates the tropical wood species from one another, highlighting their distinct colour profiles. Notably, certain thermally modified hardwoods (e.g., black locust and oak) are positioned near wengé, indicating a substantial similarity in their colourimetric characteristics. This supports the assessment presented in Tab. 1 and reinforces the notion that thermal modification can effectively replicate the optical qualities of tropical woods.

Furthermore, the clustering pattern observed in the PCA plot – such as thermally modified European beech aligning with ipé and thermally modified birch resembling more – suggests that colour coordinates alone are sufficient to distinguish between species groups while also revealing overlapping tendencies between selected thermally modified and tropical woods. This finding provides a statistical basis for recommending thermally treated temperate species as a sustainable alternative to tropical timber in decorative and design-oriented applications.

Based on the PCA assessment, four hardwood species thermally treated at 200°C for 3 hours, which exhibited a pronounced visual similarity to selected tropical woods, were positioned near them within the CIELAB space (Fig. 2).

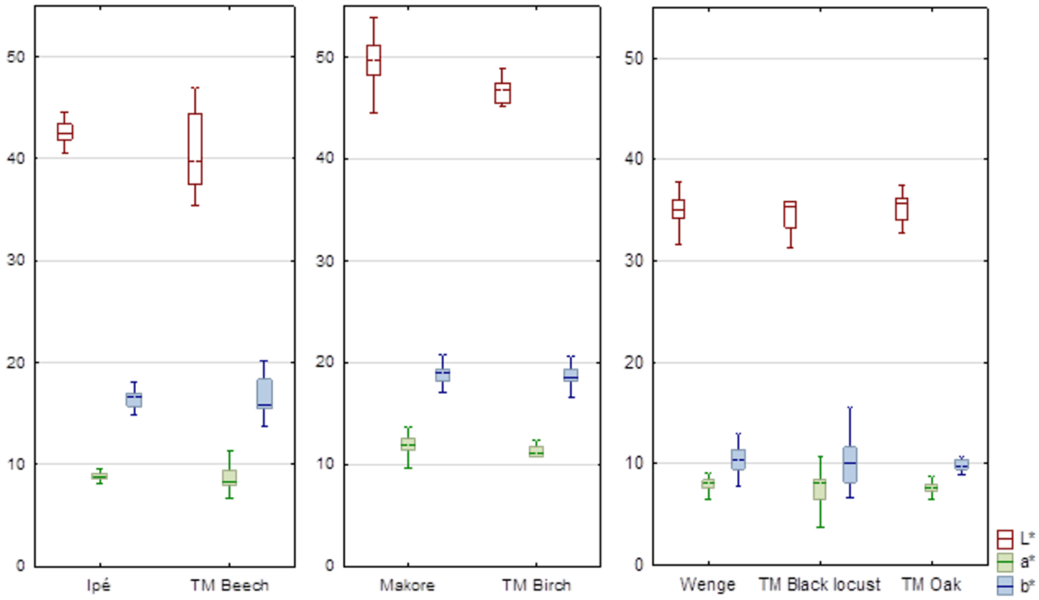

Fig. 2 Comparison of CIELAB colour coordinates for tropical and selected modified hardwoods using boxplot visualisation.

CONCLUSION

The observed colour similarity between thermally modified local hardwoods and tropical wood species demonstrates that heat treatment can effectively alter the visual appearance of temperate wood, bringing it closer to the aesthetic qualities of tropical timber.

Based on the experimental assessment, four hardwood species thermally treated at 200 °C for 3 hours exhibited a pronounced colour similarity to selected tropical woods.

European beech closely resembled ipé, while birch approximated makoré; both pedunculate oak and black locust showed a colour match with wengé. Other thermally modified hardwoods only partially mimicked the appearance of tropical wood species, indicating a need for further optimisation.

To support and visualise these similarities, a principal component analysis (PCA) was performed using L^*, a^*, and b^* colour coordinates. The first two principal components accounted for 98.93% of the total variance, clearly differentiating the tropical wood species and highlighting overlaps with selected thermally modified hardwoods. The PCA score plot confirmed the clustering of European beech with ipé, birch with makoré, and oak and black locust with wengé, providing a robust statistical basis for the visual observations.

These insights are highly relevant for the wood processing and furniture industries, offering opportunities to replace tropical wood species with thermally modified, locally sourced hardwoods, thereby combining aesthetic appeal with improved sustainability. Future research should focus on refining treatment parameters – such as temperature, duration, or pre-conditioning – to achieve a closer resemblance for a broader range of species, and to deepen understanding of the link between thermal modification and resulting colourimetric transformations.

REFERENCES

Babiak, M., Kubovský, I., Mamoňová, M., 2004. Color space of the selected domestic species. in Interaction of Wood with Various Forms of Energy, Kurjatko, S., Kúdela, J., Eds.; Zvolen: Technical University in Zvolen, 113–117.

Da Silva, R.A.F., Setter, C., Mazette, S.S., de Melo, R.R., Stangerlin, D.M., 2017. Colorimetry of wood from thirty tropical species. Ciência da Madeira (Brazilian Journal of Wood Science) 8, 1, 36–41. https://doi.org/10.12953/2177-6830/rcm.v8n1p36-41

Dudiak, M., Kminiak, R., Banski, A., Chuchala, D. 2024. The Effect of Steaming Beech, Birch and Maple Woods on Qualitative Indicators of the Surface. Coatings 14, 117. https://doi.org/10.3390/coatings14010117

Dzurenda, L., 2022. Range of color changes of beech wood in the steaming process. BioResources, 17, 1, 1690. https://doi.org/10.15376/biores.17.1.1690–1702

Dzurenda, L., 2023. Natural Variability of the Color of Beech Wood in the Color Space CIE L^* a^* b^*. Forests, 14, 6, p.1103. https://doi.org/10.3390/f14061103

Gandelová, L., Horáček., P., Šlezingerová, J., 2009. The science of wood. Mendel University of Agriculture and Forestry in Brno. 176 p.

Geffert, A., Výbohová, E., Geffertová, J. 2019. Changes in the chemical composition of oak wood due to steaming. Acta Facultatis Xylologiae Zvolen, 61, 1, 19–29. https://doi.org/10.17423/afx.2019.61.1.02

Geffert, A., Geffertová J., Dudiak, M. Výbohová, E. 2020. Influence of steaming temperature on chemical characteristics and colour of alder wood. Trieskove a beztrieskove obrabanie dreva 12, 49–56.

Hill, C. A., 2007. Wood modification: chemical, thermal and other processes. John Wiley & Sons.

Hill, C., Altgen, M. Rautkari, L., 2021. Thermal modification of wood-a review: chemical changes and hygroscopicity. Journal of Materials Science 56, 6581–6614. https://doi.org/ 10.1007/s10853-020-05722-z

Hon, D.N.-S., Minemura, N., 2000. Color and discoloration. in: Wood and Cellulosic Chemistry, 2nd ed.; Hon, D.N.-S., Shiraishi, N., Eds.; CRC Press: New York, USA, 385–442.

Hrčková, M., Koleda, P., Barcik, Š., Štefková, J., 2018. Color change of selected wood species affected by thermal treatment and sanding. Bioresources 13. https://doi.org/10.15376/biores.13.4.8956-8975

Janin, G., Gonçalez, J.C., Ananías, R., Charrier, B., Silva, G.F.D., Dilem, A., 2001. Aesthetics appreciation of wood colour and patterns by colorimetry. Part 1. Colorimetry theory for the CIE

Lab system. Maderas: Ciencia y Tecnología 3, 14. http://dx.doi.org/10.4067/S0718-221X2001000100001
Katuščák, S., Kučera, J., 2000. CIE orthogonal and cylindrical color parameters and the color sequences of the temperate wood species. Wood Research 45, 9–21.
Meints, T., Teischinger, A., Stingl, R., Hansmann, C., 2017. Wood colour of central European wood species: CIE Lab characterisation and colour intensification. European Journal of Wood and Wood Products 75, 499–509. https://doi.org/10.1007/s00107-016-1108-0
Ortiz-Hidalgo, C., Pina-Oviedo, S., 2019. Hematoxylin: Mesoamerica's gift to histopathology. Palo de Campeche (logwood tree), pirates' most desired treasure, and irreplaceable tissue stain. International Journal of Surgical Pathology 27(1), 4–14. https://doi.org/ 10.1177/1066896918787652
Sandak, A., Sandak, J., Allegretti, O., 2015. Quality control of vacuum thermally modified wood with near infrared spectroscopy. Vacuum, 114, 44–48. https://doi.org/10.1016/j.vacuum.2014.12.027
Sandberg, D., Kutnar, A., Karlsson, O., Jones, D., 2021. Wood modification technologies: principles, sustainability, and the need for innovation. CRC Press.
Slabejová, G., Šmidriaková, M., Fekiač, J., 2016. Gloss of transparent coating on beech wood surface. Acta Facultatis Xylologiae Zvolen 58, 37–44. https://doi.org/10.17423/afx.2016.58.2.04
Tolvaj, L., Persze, L., Lang, E., 2013. Correlation between hue angle and lightness of wood species grown in Hungary. Wood Research 58, 141–145.
Vidholdová, Z., Reinprecht, L., 2011. Thermowood. Šmíra-Print, 89 p.
Vidholdová, Z., Reinprecht, L., Iždinský, J., 2017. Microbial resistance of tropical woods. Zvolen: Technical University in Zvolen (in Slovak), Technical university in Zvolen, 67 p.
Vidholdová, Z., Sandak, A., Sandak, J., 2019. Assessment of the chemical change in heat treated pine wood by near infrared spectroscopy. Acta Facultatis Xylologiae Zvolen 61, 1, 31–42. https://doi.org/10.17423/afx.2019.61.1.03

ACKNOWLEDGMENT

This work was supported by the Slovak Research and Development Agency under the Contract no. APVV-21-0049 and APVV-21-0051.

AUTHORS' ADDRESSES

Ing. Zuzana Vidholdová, PhD.
Technical University in Zvolen
Faculty of Wood Sciences and Technology
Department of Wood Technology
T.G. Masaryka 24, 960 01 Zvolen
zuzana.vidholdova@tuzvo.sk

RNDr. Tatiana Hýrošová, PhD.
Technical University in Zvolen
Faculty of Wood Sciences and Technology
Department of Mathematics and Descriptive Geometry
T. G. Masaryka 24, 960 01 Zvolen
tatiana.hyrosova@tuzvo.sk