



ACTA  
SILVATICA  
&  
LIGNARIA  
HUNGARICA

AN INTERNATIONAL JOURNAL  
IN FOREST, WOOD  
AND ENVIRONMENTAL  
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## Photodegradation Properties of Earlywood and Latewood Spruce Timber Surfaces

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**Abstract** – Spruce (*Picea abies* Karst.) samples were irradiated using an ultraviolet light emitter mercury vapour lamp. The examined specimen surfaces contained earlywood or latewood to determine the photodegradation properties of these two tissue types. The generated chemical changes were monitored by diffuse reflectance Fourier transformed infrared spectroscopy. The difference spectrum method was used to present absorption changes. The earlywood suffered considerably greater degradation than the latewood during the UV irradiation. Most of the lignin molecules in the examined surface layer degraded during the first 11 days of UV irradiation for both earlywood and latewood. Results demonstrated that two types of unconjugated carbonyls absorbing at 1705 and 1764 cm<sup>-1</sup> wavenumbers were created during the photodegradation. Time dependence of the absorption changes showed correlation between the guaiacyl lignin degradation and the generation of unconjugated carbonyl group absorbing at 1764 cm<sup>-1</sup> wavenumber.

**lignin / ultraviolet irradiation / infrared spectroscopy**

**Kivonat** – A lucfenyő faanyag korai és késői pásztajának fotodegradációs tulajdonságai. Luc (*Picea abies* Karst.) famintákat világítottunk meg higanygőz lámpa által kibocsátott ultraibolya fénnel. A vizsgált minták felszíne korai- vagy késői pászta tartalmazott, hogy meghatározhassuk a kétféle pászta fotodegradációs tulajdonságait. A diffúz visszaverődésen alapuló Fourier transzformációs infravörös spektroszkópia segítségével követtük nyomon a kémiai változásokat. Az abszorpcióban bekövetkező módosulásokat a kalkulált különbségi színeképek tükrözik. A korai pászta számottevően nagyobb degradációt szenvedett az UV besugárzás hatására, mint a késői pászta. A vizsgált felületi rétegben lévő lignin molekulák többsége degradálódott az UV besugárzás első 11 napja során. Az eredmények azt mutatják, hogy kétfajta nemkonjugált karbonil csoport keletkezett a fotodegradáció során, melyek abszorpciója az 1705 és az 1764 cm<sup>-1</sup> hullámszámoknál jelentkezett. A kezelési idő függvényében vizsgált gvajacil lignin degradációja és az 1764 cm<sup>-1</sup> hullámszámnál abszorbeáló nemkonjugált karbonil csoportok keletkezése között ok-okozati összefüggést találtunk.

**lignin / ultraibolya besugárzás / infravörös színeképelemzés**

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## 1 INTRODUCTION

Colour harmony is one of nature's most beautiful creations. Machined wood surfaces in any anatomical plane present the colour diversity of the interior lumen surfaces, cell wall, earlywood, and latewood zones. The colour hue of wood between red and yellow generates a feeling of warmth.

This colour harmony of solid wood is sensitive to light, heat and humidity. Wood surfaces may degrade due to the combination of these factors and subsequently erode and become grey. Outdoor weathering tests of wood are highly complex. Outdoor weathering tests have some unavoidable disadvantages for scientific research because weather conditions are neither controllable nor repeatable. Therefore, the weathering properties of wood are usually investigated under artificial conditions.

The main factor causing the greatest changes in wood colour is exposure to sunlight (Tolvaj – Mitsui 2005, Zivkovic et al. 2014). The ultraviolet (UV) part of sun radiation causes the main degradation of wooden surfaces (Agresti et al. 2013, Yildiz et al. 2013, Borda – Popescu 2019, Liu X et al. 2016, 2019, Liu R et al. 2019). Chemical analyses showed that the deterioration is mainly related to lignin decomposition (Pandey 2005, Teaca et al. 2013, Timar et al. 2016, Arpaci et al. 2020). The chromophoric groups of lignin are strong UV light absorbers. The energy of the absorbed UV photons is enough to create free phenoxyl radicals. These free radicals react with oxygen to produce carbonyl groups (Tolvaj – Faix 1995, Bonifazi et al. 2017, Varga et al. 2017, Jankowska et al. 2020). Rain is able to leach out some parts of the degradation products. The chemical background of leaching was recently investigated (Kannar et al. 2018, Bejó et al. 2019, Varga et al. 2020, Pásztor et al. 2020). The infrared (IR) spectrum analysis showed that the leached surface suffered greater lignin degradation than the dry surface. The photodegradation-generated compounds, containing unconjugated carbonyl groups, were leachable. According to the Arrhenius law, increasing temperatures intensify the effect of photodegradation (Tolvaj et al. 2013, 2015, Varga et al. 2017, Preklet et al. 2018).

Differences in the weathering properties of earlywood and latewood are well visible after long-term outdoor exposure. Earlywood surfaces became more eroded than latewood surfaces. Though this phenomenon is mentioned in some papers (Turkulin – Sell 2002, Tolvaj et al. 2014, Sandak et al., Štěrbová et al. 2020), the chemical background has not been investigated yet.

The aim of this study was to monitor chemical changes of photodegraded earlywood and latewood surfaces. IR spectroscopy was the applied analytical tool.

## 2 MATERIALS AND METHODS

Spruce (*Picea abies* Karst.) specimens with low extractive content were chosen for the degradation test. The specimen dimensions were 30 mm x 10 mm x 5 mm (long. x tang. x rad.). Both investigated series were represented by three samples. IR measurement was completed on two fixed locations of the tangential surface of each sample (both earlywood and latewood samples). The tangential surface of the specimens contained only earlywood or latewood. A double mercury vapour lamp, with a total electric power of 800 W, as a strong UV light emitter, generated the light irradiation. The UV radiation was 80% of the total emission of the lamps. Specimens were located at a distance of 64 cm from the lamp. The temperature in the chamber was 50°C during the irradiation. The duration of the first UV irradiation period was 24 hours. After this period, UV radiation time was doubled (48 hours), and the 48-hour period of UV radiation was repeated up to 20 days (the last period was 36 hours). The shorter UV

radiation time was chosen at the beginning of the treatment because the degradation effect of UV radiation is very intensive at the beginning of the treatment.

Diffuse reflectance infrared Fourier transform (DRIFT) spectrum of the samples was measured before and after each treatment period. Measurements were carried out with an IR spectrophotometer (JASCO FT/IR 6300). The resolution was  $4\text{ cm}^{-1}$  and 64 scans were measured and averaged. The background spectrum was obtained against an aluminium plate. Two-point baseline correction at  $3800\text{ cm}^{-1}$  and at  $1900\text{ cm}^{-1}$  was executed. The spectral intensities were calculated in Kubelka-Munk (K-M) units. The spectra were normalised to the band maximum around  $1375\text{ cm}^{-1}$ . The intensity of spectra was adjusted to 1.0 by this normalisation at a maximum of around  $1375\text{ cm}^{-1}$ . This C-H band of cellulose is often used as an internal standard because of its high intensity, central position, and strong stability during photodegradation. The difference spectrum was calculated by subtracting the initial IR data from the data of the treated sample. In this case, absorption increase is represented by positive band while negative band represents absorption decrease. Details are described in a previous work (Csanady et al. 2015). The band assignment is presented in Table 1.

Table 1. Characteristic IR bands of wood (place of maximum) and band assignments (Csanády et al. 2015)

| Wavenumber<br>( $\text{cm}^{-1}$ ) | Assignment                                                                                     |
|------------------------------------|------------------------------------------------------------------------------------------------|
| 3600–3550                          | Intramolecular hydrogen bond in a phenolic group (in lignin) and weakly bounded absorbed water |
| 3360–3310                          | O(3)H. .O(5) intramolecular hydrogen bonds in cellulose                                        |
| 2928                               | CH <sub>2</sub> stretching asymmetric                                                          |
| 2854                               | Symmetric CH <sub>2</sub> stretching                                                           |
| 1770–1757                          | C=O stretching vibration of non-conjugated ketones and $\gamma$ lactones                       |
| 1736–1705                          | C=O stretching vibration of carboxyl groups and acetyl groups in hemicelluloses (xyloglucan)   |
| 1660–1653                          | conjugated C-O in quinines coupled with C=O stretching of various groups (flavones)            |
| 1628–1618                          | C=O stretching in flavones                                                                     |
| 1604–1594                          | aromatic skeletal breathing with CO stretching (syringil lignin)                               |
| 1512–1505                          | aromatic skeletal (guaiacyl lignin)                                                            |
| 1478–1476                          | C–H deformation in lignin                                                                      |
| 1465–1457                          | C–H deformation in xylan                                                                       |
| 1435                               | C–H deformation in lignin and carbohydrates                                                    |
| 1390–1380                          | C–H deformation in cellulose and hemicellulose                                                 |
| 1369–1366                          | Aliphatic C-H stretching in methyl and phenol OH                                               |
| 1333–1342                          | C–H deformation, C-OH stretching, syringyl ring                                                |
| 1319                               | C–H <sub>2</sub> wagging, C–H deformation (conifers)                                           |
| 1285                               | C–H bending mode in cellulose                                                                  |
| 1285–1275                          | C <sub>aryl</sub> -O, guaiacyl ring breathing with CO stretching                               |
| 1240–1230                          | C–O linkage in guaiacyl aromatic methoxyl groups and acetyl groups in xyloglucan               |
| 1183–1175                          | C-O-C stretching (asymm.) in cellulose and hemicelluloses                                      |
| 1158–1156                          | C–O–C stretching in pyranose rings, C=O stretching in aliphatic groups                         |
| 1138–1131                          | C-O-C stretching (symm.), arom. C-H i.p. deformation, glucose ring vibration                   |
| 1108–1106                          | C-O-C stretching                                                                               |
| 1078–1076                          | C–O stretching mainly from C(3)–O(3)H in cellulose I                                           |
| 1050–1045                          | C–O and C–C stretching in cellulose and hemicelluloses                                         |
| 898                                | C-H deformation of cellulose                                                                   |

### 3 RESULTS AND DISCUSSION

Infrared spectroscopy is a good measurement technique to determine the chemical changes of wood caused by light irradiation. *Figure 1* illustrates the IR absorption spectrum of spruce earlywood before and after three days of UV irradiation. Absorption intensities are presented in Kubelka-Munk (KM) units. The left half of the spruce absorption spectrum consists of two broad bands. The higher peak around  $3450\text{ cm}^{-1}$  belongs to the absorption of hydroxyl groups. Hydroxyl groups are located at various places in cellulose, hemicellulose, and lignin. The OH groups are located in many different positions surrounded by diverse chemical compounds. Surrounding chemical groups perturb the vibration of hydroxyl groups, which slightly modifies the wavenumber of the absorption band. That is why the hydroxyl groups have absorption at different wavenumbers causing a rather wide absorption band. Water in the wood also results in absorption in this region. The next band around  $2900\text{ cm}^{-1}$  represents the absorption of different methyl groups. This is also a multiple absorption band.

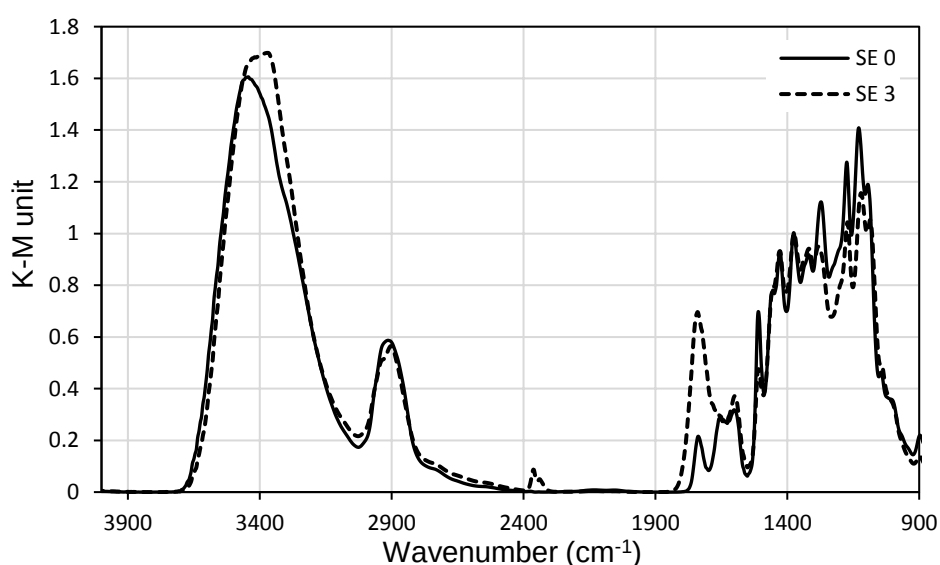


*Figure 1. Absorption spectra of spruce (S) earlywood (E) before treatment (0) and after three days of UV irradiation*

The right side of the spectrum (fingerprint region between  $900\text{--}1900\text{ cm}^{-1}$ ) consists of several overlapping bands generated by the absorption of cellulose, hemicelluloses, and lignin. As the bands highly overlap each other, most of the peak maxima are not real due to the superposition of two or more individual bands. (This phenomenon is clearly visible when comparing the form of the bands around  $1740\text{ cm}^{-1}$  in *Figures 2–4*.)

The unconjugated carbonyl band is located between  $1650$  and  $1820\text{ cm}^{-1}$ . This carbonyl band is the superposition of some individual bands. A previous study determined four bands in the unconjugated carbonyl region (Varga et al. 2017). Hence most publications treat the band of unconjugated carbonyls as a single absorption band with a maximum around  $1740\text{ cm}^{-1}$ . The region between  $950\text{--}1550\text{ cm}^{-1}$  wavenumbers has many overlapping bands. The most important peaks are the following: the peaks of the aromatic ring vibrations arising from lignin are at  $1510\text{ cm}^{-1}$ ; the peaks of the aromatic C-H deformation are at  $1469$  and  $1428\text{ cm}^{-1}$ ; the absorption of the guaiacyl ring breathing is located at  $1270\text{ cm}^{-1}$ .

The absorption wavenumbers of the asymmetric and symmetric stretching of ether bond in cellulose are located around  $1170$  and  $1130\text{ cm}^{-1}$ . The aromatic C-H deformation and the glucose ring vibration also generate absorption around  $1130\text{ cm}^{-1}$ .

Chemical changes created by UV irradiation can be seen in *Figure 1*. The number of hydroxyl groups absorbing around  $3400\text{ cm}^{-1}$  increased and the groups absorbing around  $3600\text{ cm}^{-1}$  decreased during the three-day UV irradiation period. A great absorption increase appeared around  $1740\text{ cm}^{-1}$ . The place of maximum shifted towards smaller wavenumbers and the band became wider. The absorption decrease of aromatic skeletal vibration of lignin at  $1510\text{ cm}^{-1}$  is hardly visible together with the absorption decrease of ether bonds between  $1120\text{--}1180\text{ cm}^{-1}$ . The difference spectrum method solves these problems. Creating the difference spectrum (irradiated minus initial) provides a more transparent figure since only those absorption bands appear where actual changes occurred. (The absorption increase is represented by positive band while negative band represents the absorption decrease.) The real changes are clearly visible in *Figure 2*, where the difference spectra are presented for both earlywood and latewood generated by one-day and three-day UV irradiation. The negative peak at  $1510\text{ cm}^{-1}$  belongs to the aromatic skeletal vibration of guaiacyl lignin. This negative peak is detectable together with the absorption decrease of the aromatic C-H deformation at  $1470$  and  $1430\text{ cm}^{-1}$  and with the absorption decrease of the guaiacyl ring breathing at  $1270\text{ cm}^{-1}$ . The greatest absorption decrease is visible at  $1174$  and  $1133\text{ cm}^{-1}$ . The first decrease belongs to the asymmetric stretching of ether bond in cellulose. The second decrease belongs to the symmetric stretching of ether bond, the aromatic C-H deformation, and to the glucose ring vibration. These absorption decreases indicate the ether splitting and the depolymerisation of cellulose.

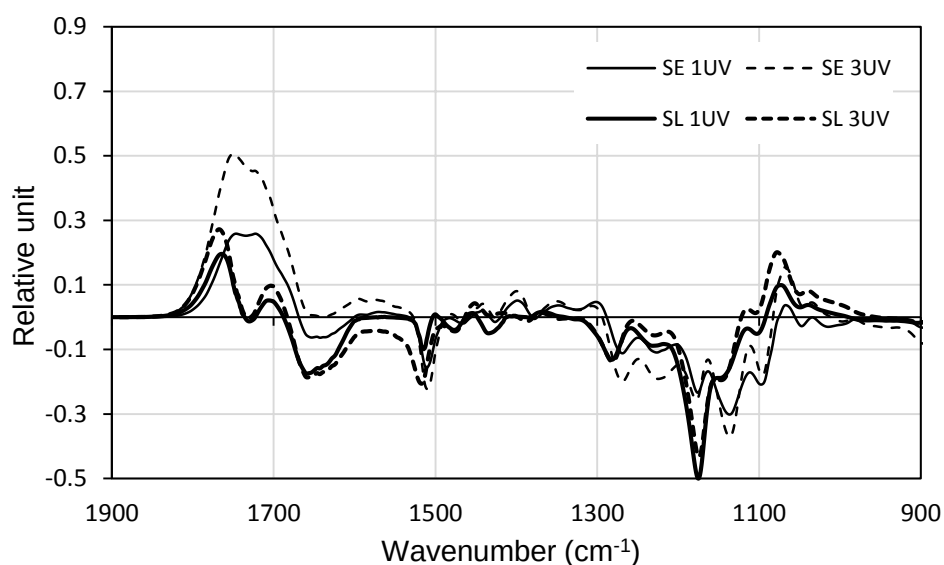


*Figure 2. Absorption difference spectrum of spruce (S) earlywood (E) and latewood (L) generated by UV irradiation (in days).*

Free radicals were generated during lignin degradation. These free radicals react with oxygen to produce carbonyl groups. The absorption increase of unconjugated carbonyls is visible in *Figures 2–4* in the  $1680\text{--}1820\text{ cm}^{-1}$  wavenumber interval. Two bands rose in this region for both earlywood and latewood at  $1705$  and  $1764\text{ cm}^{-1}$  wavenumbers. The band at  $1764\text{ cm}^{-1}$  represents the absorption of CO stretching for unconjugated ketones and  $\gamma$  lactones generated by the oxidation after the splitting of the aromatic ring. The band at  $1705\text{ cm}^{-1}$  represents the absorption of aliphatic carboxyl groups. Although the locations of these peaks should be the same, the intensities and the apparent places of the peaks are different for earlywood and latewood. Latewood produced a smaller absorption increase than earlywood. Great intensity difference was found between the two peaks. The peak intensity at  $1705\text{ cm}^{-1}$

was small compared to the neighbouring peak. The two bands are well separated because of the low intensities. In contrast, the peak intensity at  $1705\text{ cm}^{-1}$  for earlywood is almost equal to that of the neighbouring peak at  $1764\text{ cm}^{-1}$ . The superposition of the two bands is visible in *Figure 2*. The real positions of the peaks are not visible since the superposition pulled the locations of the peaks toward each other. These two bands finally joined into one single band after 20-day UV irradiation (*Figure 4*). The negative intensity change of the peak at  $1510\text{ cm}^{-1}$  increased during UV irradiation. (Time dependence of this intensity will be discussed later.)

The intensity of the two types of ether bond at  $1174$  and  $1133\text{ cm}^{-1}$  decreased, but in different ways for earlywood and latewood. The two negative peak intensities were almost equal for earlywood. The peak at  $1133\text{ cm}^{-1}$  was a little greater than the peak at  $1174\text{ cm}^{-1}$ . Latewood showed opposite peak intensities. The peak at  $1174\text{ cm}^{-1}$  presented the greatest negative change and the peak at  $1133\text{ cm}^{-1}$  is visible as a shoulder. There is a visible positive peak at  $1068\text{ cm}^{-1}$ . This positive peak is associated with the C-O bonds stretching in cellulose and hemicelluloses.

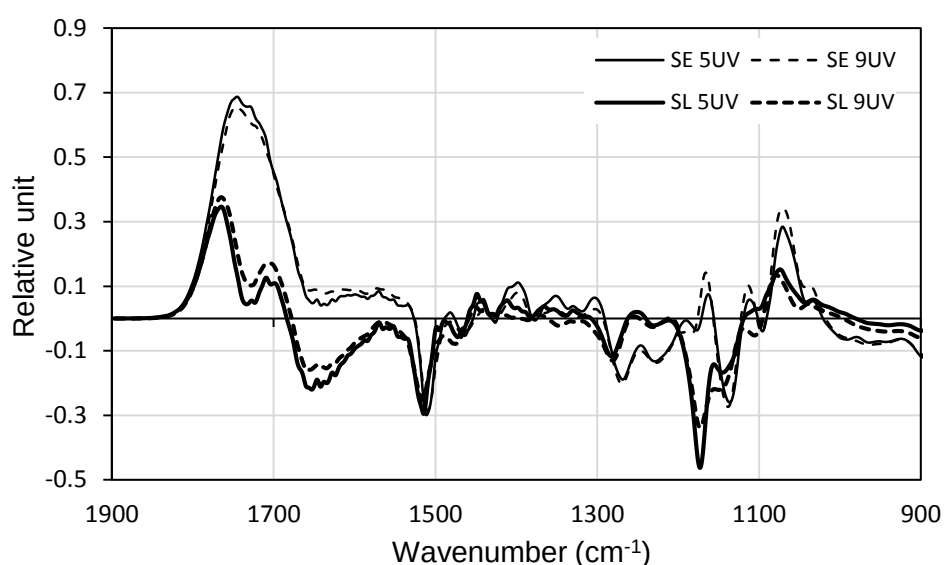


*Figure 3. Absorption difference spectrum of spruce (S) earlywood (E) and latewood (L) generated by UV irradiation (in days)*

The prolonged treatment time intensified the absorption changes (*Figures 3 and 4*). The absorption intensities of the two types of unconjugated carbonyl groups at  $1705$  and  $1764\text{ cm}^{-1}$  wavenumbers increased with longer irradiation. (The time dependence of these intensities will be discussed later.) The two bands composed a single band after nine days of irradiation for earlywood, which remained up to the end of treatment. The peak intensity at  $1705\text{ cm}^{-1}$  was growing faster than the peak intensity at  $1764\text{ cm}^{-1}$  for latewood, and it became only a shoulder after 20 days of irradiation.

The evaluation of the changes in the ether bond region is difficult because the Kubelka-Munk equation does not provide the absorption spectrum properly if the absorption is high and the surface roughness changes. A previous study showed that photodegradation increases the surface roughness of wood (Tolvaj et al. 2014). The roughness increase lifts up the intensities due to the increasing scattering. A detailed discussion of this phenomenon can be found in a previous study (Tolvaj et al. 2011). The lifting effect overlaps the real absorption changes, interfering with the evaluation of IR spectrum in the  $1000\text{--}1200\text{ cm}^{-1}$  wavenumber interval.

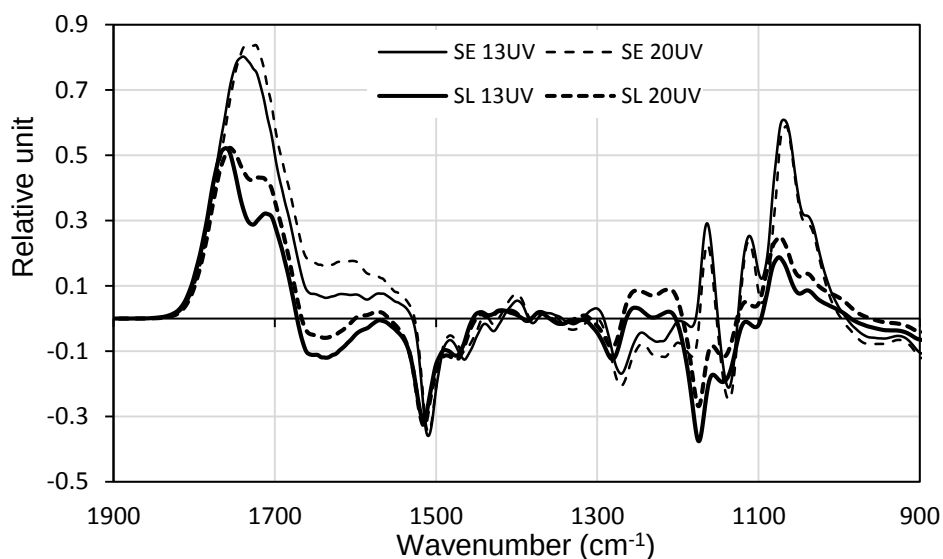


Figure 4. Absorption difference spectrum of spruce (S) earlywood (E) and latewood (L) generated by UV irradiation (in days).

Figures 2–4 present the absorption decrease of guaiacyl lignin. However, due to overlapping, these figures do not clearly show the intensity changes of this negative peak. Figure 5 clearly demonstrates the absorption change at  $1510\text{ cm}^{-1}$  in all investigated situations. The results show that earlywood suffered greater lignin degradation than latewood. The higher extractive content in latewood provided greater protection for lignin than the lower extractive content in earlywood. The protecting effect of the extractives was demonstrated by previous studies (Németh et al. 1992, Varga et al. 2020). Lignin degradation was fast at the beginning of the treatment and stopped after 11 days of UV irradiation for both earlywood and latewood. The reason could be that most of the lignin molecules of the examined surface layer degraded during the first 11 days of UV irradiation.

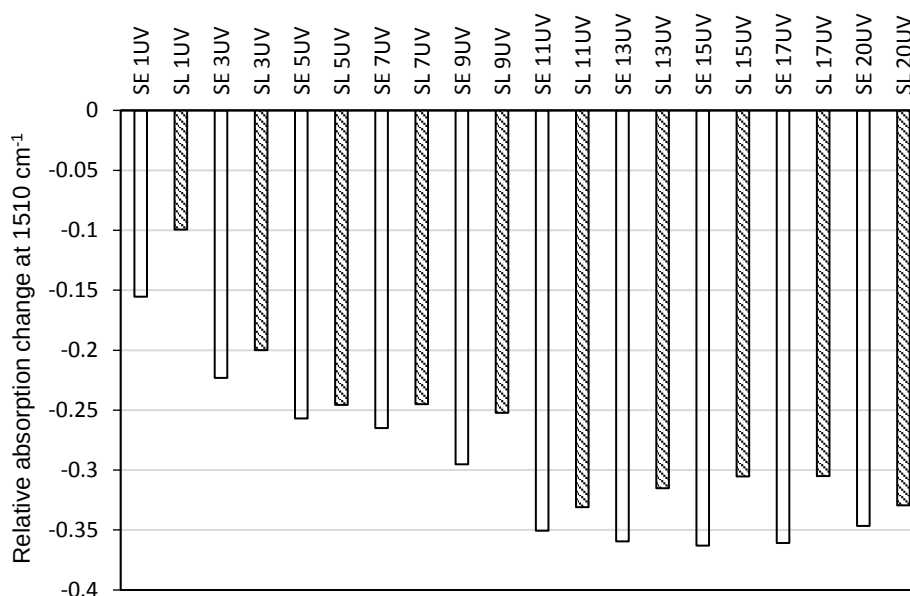


Figure 5. Absorption band intensity change of guaiacyl lignin in spruce (S) earlywood (E) and latewood (L) at  $1510\text{ cm}^{-1}$  wavenumber generated by UV irradiation (in days)

Figure 6 presents the intensity changes of the unconjugated carbonyl groups absorbing at the  $1764\text{ cm}^{-1}$  wavenumber. Absorption intensity increased continuously for both earlywood and latewood up to the thirteenth day of UV irradiation, and decreased slightly after that. The decrease after the thirteenth day of treatment might not be a real decrease. The values were read exactly at  $1764\text{ cm}^{-1}$  wavenumber; however, changes in the overlapping band at the  $1705\text{ cm}^{-1}$  wavenumber probably modified the real values. UV irradiation generated greater absorption increase for earlywood than for latewood. The trend seems to be opposite for one-day treatment, while Figure 2 clearly shows that earlywood produced greater absorption increase than latewood during the first day of irradiation. The tendency of the absorption changes at  $1764\text{ cm}^{-1}$  was a mirror image of lignin degradation at  $1510\text{ cm}^{-1}$ . This fact demonstrates the correlation between lignin degradation and the generation of unconjugated carbonyl groups absorbing at  $1764\text{ cm}^{-1}$ . Many studies deal with the correlation between lignin degradation and the generation of new unconjugated carbonyl groups (Pandey 2005, Agresti et al. 2013, Timar et al. 2016, Bonifazi et al. 2017, Reinprecht et al. 2018). However, all of these publications use the complete integrated unconjugated carbonyl band as the participant in the correlation. Our results demonstrate that only one component of unconjugated carbonyl band (at  $1764\text{ cm}^{-1}$  wavenumber) participates in this correlation.

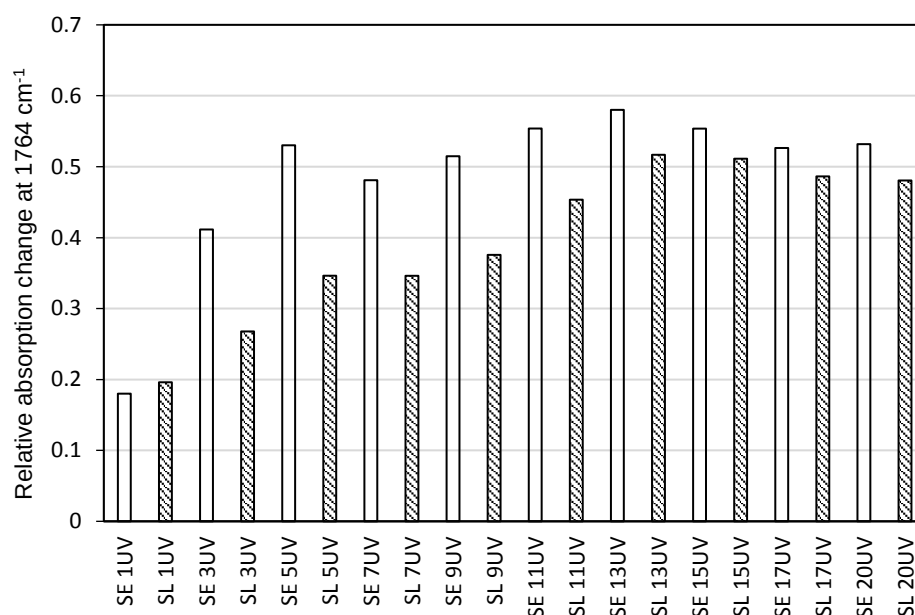


Figure 6. Absorption band intensity change of the unconjugated carbonyls at  $1764\text{ cm}^{-1}$  for spruce (S) earlywood (E) and latewood (L) generated by UV irradiation (in days)

Figure 7 shows the irradiation time dependence of the unconjugated carbonyls absorbing at the  $1705\text{ cm}^{-1}$  wavenumber. Earlywood presented rapid absorption increase at the beginning of the UV irradiation, followed by a moderate increase up to the end of the treatment. Latewood produced only a small absorption increase during the first day of irradiation. This small value was followed by continuous absorption increase throughout the whole investigated treatment period. In the second part of the treatment, latewood produced more intensive absorption increase than the earlywood. The absorption increase at  $1705\text{ cm}^{-1}$  does not show similar time dependence to the lignin degradation. This finding raises the question of whether the unconjugated carbonyls absorbing at  $1705\text{ cm}^{-1}$  are derived from the degradation of lignin. This phenomenon requires further chemical investigations.

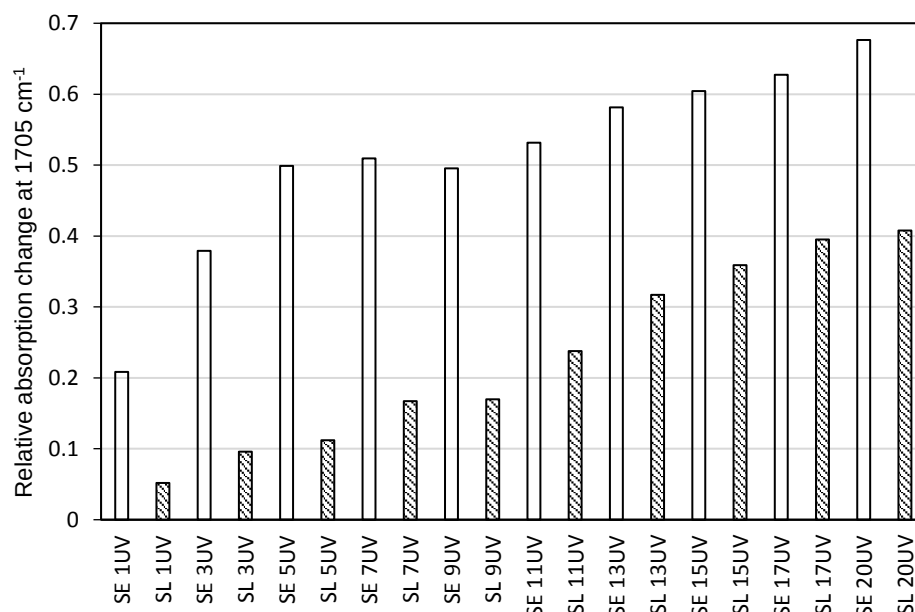


Figure 7 Absorption band intensity change of the unconjugated carbonyls at  $1705\text{ cm}^{-1}$  for spruce (S) earlywood (E) and latewood (L) generated by UV irradiation (in days)

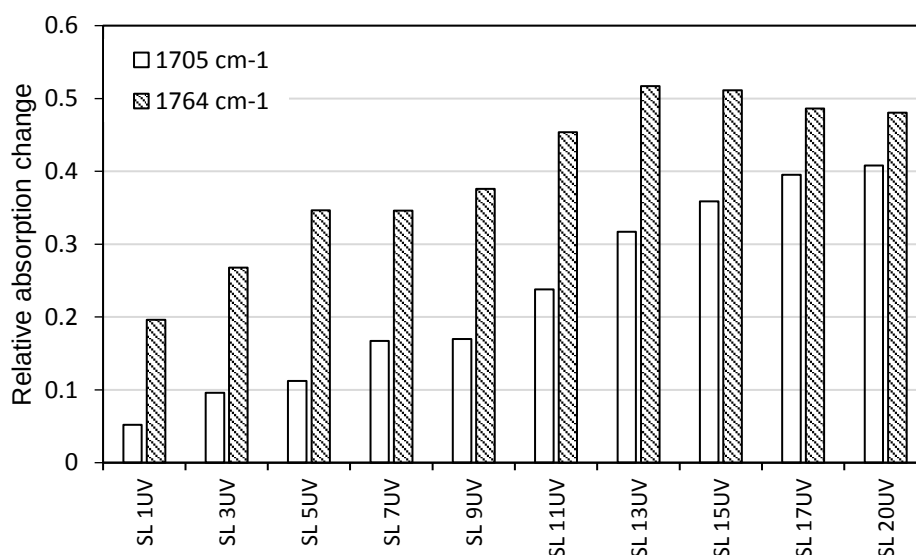


Figure 8. Absorption band intensity change of the unconjugated carbonyls at  $1705\text{ cm}^{-1}$  and  $1764\text{ cm}^{-1}$  wavenumbers for spruce (S) latewood (L) generated by UV irradiation (in days)

Figure 8 represents the differences between the absorption properties of the two types of unconjugated carbonyl groups absorbing at  $1705\text{ cm}^{-1}$  and  $1764\text{ cm}^{-1}$ . The time dependence of these two absorption increases is completely different. The band at  $1764\text{ cm}^{-1}$  showed a rapid increase at the beginning of the UV irradiation. The change of the absorption increase produced a maximum on the thirteenth day of the treatment. In contrast, the band at  $1705\text{ cm}^{-1}$  presented continuous increase during the whole investigated period. This difference in the growing tendency shows that the generation of these two types of unconjugated carbonyl groups (at  $1705\text{ cm}^{-1}$  and  $1764\text{ cm}^{-1}$ ) has two different pass ways or different origins.

## 4 CONCLUSIONS

Spruce samples with earlywood or latewood surfaces were irradiated using a strong ultraviolet light emitter mercury lamp. Chemical changes were monitored by DRIFT IR spectroscopy. The difference spectrum method was applied to determine the changes. Lignin deterioration and unconjugated carbonyl compound generation were found to be the main changes during UV irradiation. Earlywood suffered greater degradation than latewood. Most of the lignin molecules of the examined surface layer degraded during the first 11 days of UV irradiation in both earlywood and latewood. Results demonstrated that two types of unconjugated carbonyls absorbing at 1705 and 1764  $\text{cm}^{-1}$  wavenumber were created during photodegradation. The time dependence of the absorption changes showed correlation between the guaiacyl lignin degradation and the generation of unconjugated carbonyl group absorbing at 1764  $\text{cm}^{-1}$  wavenumber. There is no correlation between the lignin degradation and the generation of unconjugated carbonyl group absorbing at 1705  $\text{cm}^{-1}$  wavenumber.

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## Comparative Study of Conventional and Zero-joint Edgebanding

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**Abstract** – Edgebanding affects both the visual appearance and edge protection of wood-based panels. In order for edgebanding to provide the desired protection, it must adhere strongly to the entire surface of the panel edges and maintain this adhesion throughout the life of the product. The present research compares conventional and so-called zero-joint edgebandings in terms of water and steam resistance, and examines the environmental impacts of edgebanding technologies using Life Cycle Assessment (LCA). In-line with our hypothesis, our test results showed that corners are the critical points of edgebanded furniture fronts, especially when exposed to moisture. Due to high variations in measurements, there is no significant difference between the two edgebanding methods at the beginning. However, differences become more significant after longer treatment times. These differences amount to two quality categories after 6 hours and three quality categories after 12 and 24 hours. The edgebanded fronts exposed to water for less than 30 minutes experience no significant deteriorations with any of the edgebanding methods. In the case of steam resistance, zero-joint edgebanding provides better protection, especially after the second and third treatment cycle. We can state that the surplus costs of zero-joint technology are 1.45 times greater than costs associated with conventional technology. Both show the considerable costs of edging materials, chipboard, and electrical energy. The applied environmental life cycle assessment (LCA) method corresponds to the requirements of ISO 14040:2006 and ISO 14044:2006 standards. We built up the environmental inventory and the life cycle model of the manufacturing technology using the GaBi Professional LCA software. In the impact assessment, we analysed the specific environmental impact categories of the differing production processes by technology according to the operation order of the manufacturing technology. In relation to traditional and the zero-joint edging technologies, according to all impact assessment methods, the life-cycle contribution rate was uniformly 47% traditional – 53% zero-joint by impact category. The higher indicator values of the zero-joint method are due to larger edge material consumption and higher energy demand. Zero-joint technology appears to avoid the application of conventional hot melt adhesives, but replacing these adhesives does not necessarily result in better environmental indicators. Nevertheless, zero-joint edgebanding does not just improve aesthetic appearance but also exceeds the durability provided by conventional edgebanding technology.

**edgebanding / resistance to water and steam / environmental impact / LCA**

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**Kivonat – Hagyományos és fugamentes élzárás összehasonlító vizsgálata.** A faalapú lemezek élzárása nemcsak esztétikailag, hanem az élek védelme szempontjából is fontos. Ahhoz, hogy az élzárás a kívánt védelmet nyújtsa erősen kell tapadnia a lemezek élének teljes felületéhez, és ezt a tapadást meg kell őriznie a termék teljes életciklusa alatt. Jelen kutatás a hagyományos és az ún. nullfugás élzárásokat hasonlítja össze a vízzel és gőzzel szembeni ellenállás szempontjából, valamint az élzárási technológiák környezeti hatásait vizsgálja. A vizsgálati eredmények azt mutatják, hogy a hipotézisünknek megfelelően a sarkok a kritikus pontok, a víz és gőz behatolása itt a leggyorsabb. A mérési adatok nagy szórása miatt a vízzel szembeni ellenállás esetén a két élzárási technológia között nincs szignifikáns különbség, azonban a 6 órás kitettség után két, a 12 és 24 órás kitettség után pedig három minőségi osztálykülönbség tapasztalható. Ha a víz csak maximum 30 percig érintkezik az éllel, nem tapasztalhatók elváltozások egyik élzárási módszernél sem. A gőzzel szembeni ellenállás esetén a nullfugás élzárás jobb védelmet nyújt különösen a második és harmadik gőzölési ciklus után. A kutatás során elvégeztük az életciklus költség-számítást is: a nullfugás technológia 1,45-szörös költség-többletet mutatott a hagyományoshoz képest. Nagyságrendileg mindkét esetben az élzáró anyag, a forgácslap és az elektromos energia költségei voltak jelentősek. A környezeti életciklus elemzés (LCA) során az ISO 14040-44:2006 szabványok alapján kizárólag az élzárási alternatívák műveleteit vizsgáltuk. Szoftveres támogatással felépítettük a gyártástechnológiák környezeti leltáradatbázisát és LCA modelljét. A hatásértékelés során technológiánként elemeztük a gyártási folyamatok jellemző környezeti hatáskategóriáit. A hagyományos és nullfugás élzárási technológiát illetően hatásértékelési módszerként egységesen 47% hagyományos - 53% nullfugás arány volt tapasztalható az életciklus hozzájárulásban hatáskategóriánként. A nullfugás eljárás magasabb értékei a nagyobb mennyiségű felhasznált élanagnak és a nagyobb energiaigénynek tudhatók be. A nullfugás technológia a hagyományos ragasztóanyag alkalmazását mellőzi, ám ennek kiváltása nem eredményezett kedvezőbb környezeti mutatókat. Az élzárások esetén életciklus elemzéssel vizsgált környezeti hatásokat nemcsak az alkalmazott gyártástechnológiák jellemzői befolyásolják, hanem emellett meghatározó szerepe van az élzárt termék igénybevételekkel szembeni tartósságának is, amely az élzárási alternatíva sajátossága.

**élzárás / vízzel és gőzzel szembeni ellenállás / környezeti hatás / LCA**

## 1 INTRODUCTION

Wood and wood-based materials are a renewable resource and are considered ‘environmentally friendly’ compared to other materials (Lippke et al. 2004). Wood product manufacturing results in lower emissions than the manufacturing of other materials (Lippke et al. 2019).

The furniture industry has been increasing its use of particleboard over the past few decades. Many studies support the main importance of edging as a mandatory technological step for protecting sides of wood composite panels such as particleboard (Jivkov 2002; Tankut & Tankut 2010; Saçlı 2015; Merdzhanov 2018).

Different technologies are currently employed for edgebanding. Gluing edgebands, which has become a key technology in furniture production, is completed through a conventional bonding process: hot melt glues are applied using rollers in edgebanding woodworking machines (Rechner et al. 2009). Technological modernization has led to the quick spread of innovative processes in furniture manufacturing. One such innovation is zero-joint edgebanding, which is considered an important technological operation in the wood industry. The main differences between the two edgebanding technologies are aesthetical appearance and adhesive spreading. The zero joint glue line is almost invisible due to the coextruded functional layer. Moreover, an additional bonding agent is unnecessary (*Figure 1*). Consequently, the environmental significance of the method is beyond question.

In edgebanding that incorporates laser technology, laser radiation melts a predetermined layer of the edging material. According to Rechner et al. (2009), laser technology for the edgebanding process in furniture manufacturing provides the same strength as conventional gluing, all without the adhesive joints that affect visual appearance. The transition between the

edgeband and the board surface provides a flawless appearance to the human eye. At the same time, the impact of external influences (like water or dirt) is reduced to a minimum. This increases the resistance of the adhesive bond to ageing (Rechner et al. 2009).

According to Tankut and Tankut (2010), the purpose of edgebanding is to suppress the absorption of water and humidity and provide an aesthetic finish for all decorative surfaces.

Edgebanding has two main functions: to cover the aesthetically unfavorable core panels like particleboard, fiberboard, etc., and to protect these panels from mechanical and physical impacts (Molnárné 2002). To fulfill these requirements, edgebanding materials (coiled foils from polyvinyl chloride [PVC], acrylonitrile butadiene styrene [ABS], polypropylene [PP], polymethylmethacrylate [PMMA], or strips from solid wood) must be perfectly bonded to the panel edges without voids or loose parts, leveled to the thickness of the panels, and trimmed to the desired dimensions and shapes. Several factors influence the durability of the adhesion line between edgebanding materials and panels. Among these we find the resistance to moisture, which affects edgebanding in two main forms i.e., liquid and vapor.

In addition to durability, the quality (conformity) factors of the product include other characteristics, such as aesthetics or environmental impacts. Life-Cycle Assessment (LCA) is the most suitable method for determining the environmental impacts of a product. According to Fava et al. (1994), the development of the LCA methodology has helped to quantify and provide information about products where environmental qualities were lacking.

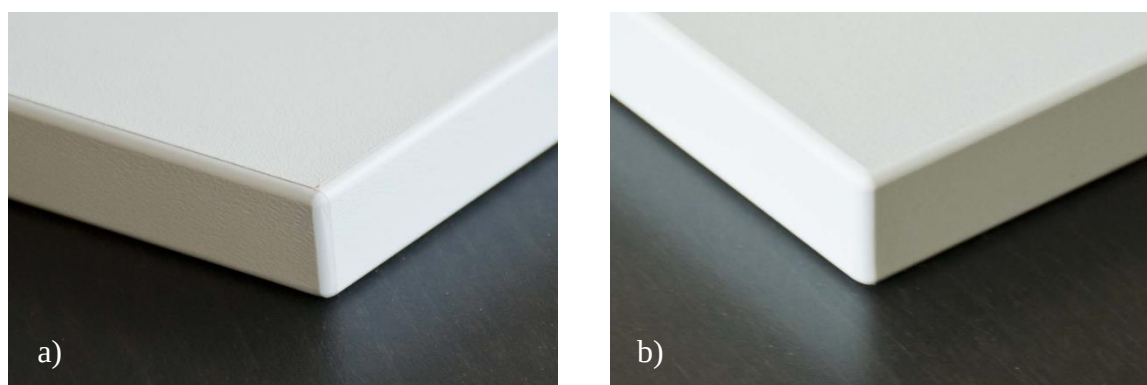


Figure 1. Aesthetic comparison of conventional (a) and zero-joint (b) ABS edgebanding

The first main goal of this research was to examine how moisture affects the durability and aesthetics of edgebanded panels. Moisture came into contact with the surface in two forms: cold liquid and hot steam. Conventional (EVA) and zero-joint technologies were used to determine the effect of edgebanding type on thickness swelling. The second goal of our study was to use the LCA method to determine and compare the environmental impacts of conventional and the zero-joint edgebanding technologies in the wood industry. Durability affects the environmental impacts additionally. If the edgebanding is more durable, the edgebanded panel is favourable in terms of environmental impacts.

## 2 MATERIALS AND METHODS

Hungarian furniture manufacturers most frequently use 18 mm-thick laminated particleboards; hence, these were selected for both the durability and environmental studies. Acrylonitrile butadiene styrene (ABS) was the material selected for edgebanding. The edgebanding methods employed were the conventional (using hot melt adhesive EVA) and zero-joint technology methods. A Roxyl 6.0 edgebander wood machine was used for both conventional and zero-joint edgebanding. Life-Cycle Analysis (LCA) was used to determine environmental impacts. We

used the GaBi Professional LCA software, which is the most trusted product for Life Cycle Assessment.

## 2.1 Durability study

All tests were performed according to the IOS-TM-0002 IKEA specification.

### 2.1.1 Assessment of edges' resistance to water

This test simulates the water resistance of the edgebanded furniture fronts used in locations with elevated humidity levels such as kitchens and bathrooms. Five specimens were used per edgebanding technology. The 400x300 mm edgebanded specimens were conditioned at  $23 \pm 2$  °C and  $50 \pm 5\%$  humidity prior to testing. Seven measuring points were selected for specimen' thickness determination: five at the edge and two at a distance of 20 mm from the edge. The first and last measuring points at the edge were located at the corners of the specimens, and the distance between each point was 100 mm. *Figure 2* shows the placement of the measuring points.

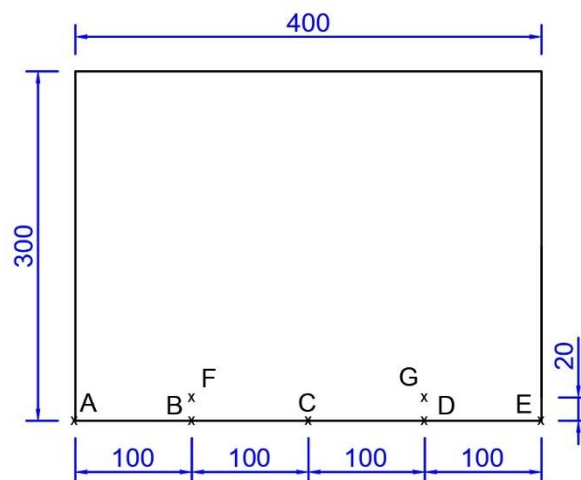


Figure 2. Measuring points of water and steam resistance

Sample thickness was determined at the measuring points to the nearest 0.01 mm using a digital caliper after conditioning and before the tests began. A 50 mm-thick, open-cell polyurethane foam with a density of 20 kg/m<sup>3</sup> was placed in a flat tub equipped with spacer plates of the same height as the tub height (50 mm), and the tub was filled with distilled water at  $23 \pm 2$  °C. Water level was kept constant at 12 mm below the upper edge of the spacers throughout the entire test period. The edgebanded specimens were placed vertically on the partition plates and exposed for the time corresponding to the test periods (*Figure 3a*). A total of seven test periods with the following values were used: 5 min, 30 min, 2 h, 6 h, 12 h, 24 h, and 48 h. The last period consisted of 24 hours of soaking and 24 hours of conditioning. After each test period, the specimen edges were wiped dry and the thickness was measured at the measurement points. After visual inspection of the edges, the thickness swelling results were evaluated on a scale of 1 to 5 as defined in the specification (*Table 1*).

Table 1. Assessment criteria for water resistance (IOS 2017)

| Rating | Criteria                                                                                                                                                                                                                                              |
|--------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 5      | <b>No visible damage</b> can be seen; thickness swelling is less than 0.05 mm.                                                                                                                                                                        |
| 4      | <b>Minor damage</b> that does not affect function or appearance essentially is accepted. The maximum thickness swelling is 0.1 mm, but without visible cracking or opening between edge bands.                                                        |
| 3      | <b>Moderate damage</b> with thickness swelling from 0.1 to 0.25 mm. The glue line may have become soft, but there is still enough adhesive to keep the edging in place. The edging may loosen to mechanical strain and few narrow cracks are allowed. |
| 2      | <b>Significant damage</b> with thickness swelling from 0.25 to 1.0 mm. Open glued joint or partly loose edging. Several narrow cracks may appear.                                                                                                     |
| 1      | <b>Severe damage:</b> thickness swelling is over 1 mm. Loose edging, totally or partly damaged surface finish. Many narrow cracks or one or more broad cracks.                                                                                        |

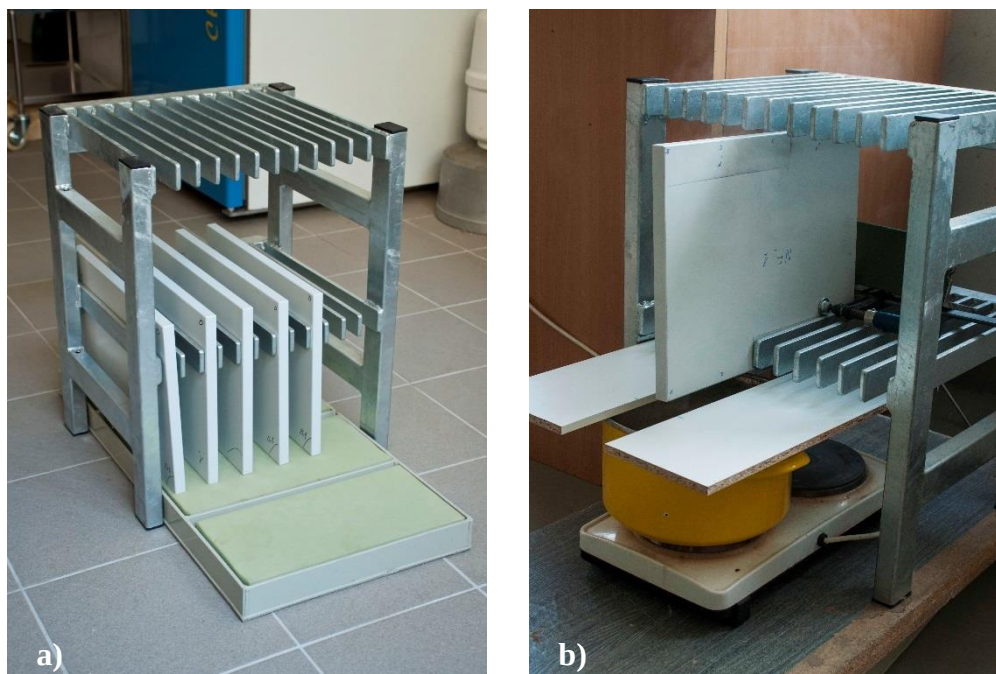


Figure 3. Determination of edge resistance to water and steam (a – to water; b – to steam)

### 2.1.2 Assessment of edges' resistance to steam

The test method simulates the effect of steam and condensation on edgebanded furniture fronts. Edgebanded specimens with dimensions of 400x300 mm were cleaned prior to conditioning (see the test method for water resistance test) and examined for defects. Sample thickness was measured at the corner and at a distance of 100 mm from the corner. Specimens were mounted on the jig using a clamp with the tested edge facing downward and resting on the water-bath with the corner at a distance of 50 mm from bath side. The length of the exposed edge was about 150 mm. The water bath placed beneath specimens was heated using an electric hob, with the water level set at 70 mm below the edge of the test samples. The water bath was covered with two panels allowing a 70 mm wide gap for specimens (Figure 3b). After five minutes of steam exposure and 24 hours conditioning, specimen thickness was measured at two measuring points. This cycle was repeated two more times, with the cumulated steam exposure time

reaching 15 minutes. After each cycle, the tested edges were examined for damage. At the end of the three cycles, the tested edges were assessed according to *Table 2*.

*Table 2. Assessment criteria for steam resistance (IOS 2017)*

| Rating | Criteria                                                                                                                  |
|--------|---------------------------------------------------------------------------------------------------------------------------|
| 5      | <b>No visible damage.</b>                                                                                                 |
| 4      | <b>Minor change:</b> slight discoloration, rough surface, minor gloss change.                                             |
| 3      | <b>Moderate change:</b> minor blistering, small cracks and opening (maximum 1 mm), visible/noticeable thickness swelling. |
| 2      | <b>Significant change:</b> opening of maximum 2 mm, large cracks, the edge band is partly loose.                          |
| 1      | <b>Severe change:</b> large opening (>2 mm), large cracks along/across the edge, edge band completely detached.           |

## 2.2 Environmental study

The objective of the environmental study was to perform a comparative life cycle analysis of conventional and zero-joint edgebanding technologies. The study refers of 3.5 m<sup>3</sup> quantity chipboard, edgebanded with two different types of ABS materials for conventional and zero-joint edging technologies. The input and output data for this study are presented in *Table 4*. The data sources stem from Hungarian manufacturing data, our own data, expert estimations, and published data. Reference period: 2016.

The applied environmental life cycle assessment (LCA) method corresponds to the requirements of ISO 14040:2006 (ISO 2006a) and ISO 14044:2006 (ISO 2006b) standards.

The environmental life cycle assessment (LCA) method plays an important role in the analysis of environmental impacts. Life cycle assessment enables the determination of the sustainability and environmental quality of wood products and the related manufacturing technologies.

Life-cycle methods allow for the evaluation of environmental burdens such as air and water pollution, solid waste, and ecosystem impacts (Lippke et al. 2019).

To run LCA, we examined the flow of material and energy on the input and output side during the conventional and zero-joint wood edgebanding operations. We also examined each material cost during the analysis.

We built up the environmental inventory and the life cycle model of the manufacturing technology using the GaBi Professional LCA software. In the impact assessment, we analysed the specific environmental impact categories of the differing production processes by technology according to the order of operation of the manufacturing technology. For a reliable analysis, we calculated the impact-category indicator results by using several impact assessment methods and models (CML2001, Primary energy).

Functional unit: edgebanding the chipboard elements of the specific furniture family with ABS edgebanding material

- reference flow (conventional): ABS edge material, 1006.98 m long, 2.00 mm thick, 22.65 mm wide
- reference flow (zero-joint): ABS edge material, 1006.98 m long, 2.35 mm thick, 23.15 mm wide

As regards the transport of raw materials, we considered 100 tkm and a EURO 4 truck. In the case of electrical energy, we used the Hungarian energy mix.

The edgebanding process steps (operational steps) of the Roxil 6.0 edgebander wood machine, which are also the LCA boundaries, comprise the following: raw materials transport – loading of banding material – chipboard surface handling – chipboard edge milling – applying glue (gluing) (*omitted for zero-joint technology*) – applying banding material by pressing (bonds the edge banding to the substrate) – end-cutting banding material – rough and fine trimming – edge rounding – ABS edge refining – glue scraping (*omitted for zero-joint technology*) – cutting grooves or rabbets (if necessary) – edge polishing using brush – edge heating for colour correction using air blower – panel transport (Kozák 2006).

### 3 RESULTS AND DISCUSSION

#### 3.1 Water resistance

Specimen thicknesses were measured in the assigned points after each treatment. F-tests and Student t-tests were employed for the statistical analysis of the data. *Figure 4* presents the variation of thickness swelling in function of treatment time, edgebanding technologies, and measurement points. From the three-dimensional column diagram, we can deduce that visible changes occur only at the corners (points A and E) and at a distance of 100 mm from the left corner (point B). The thickness swelling at point B is remarkable only in conventional joints; there are no visible changes at zero joints. Both joint types were waterproof for 30 minutes. The first noticeable deviations occurred after two hours of exposure. The maximum thickness swelling of 1.31 mm was measured at the corner of the conventional joints after 24 hours of treatment. In point A (specimens' left corner) there were no statistically significant differences between conventional and zero joints. However, at a distance of 100 mm from the corner (point B) after 2 hours of water exposure, the conventional joints swelling was 0.112 mm and increased gradually with the exposure time, but the zero joints showed no changes in thickness. At the right corner (point E), the visible changes appeared just after 6 hours of exposure and the zero joints had higher swelling values than conventional joints. After 24 hours of exposure and 24 hours of conditioning, the specimens started to lose water in the conditioning phase and the thickness values began to decline; however, this change was not statistically significant.

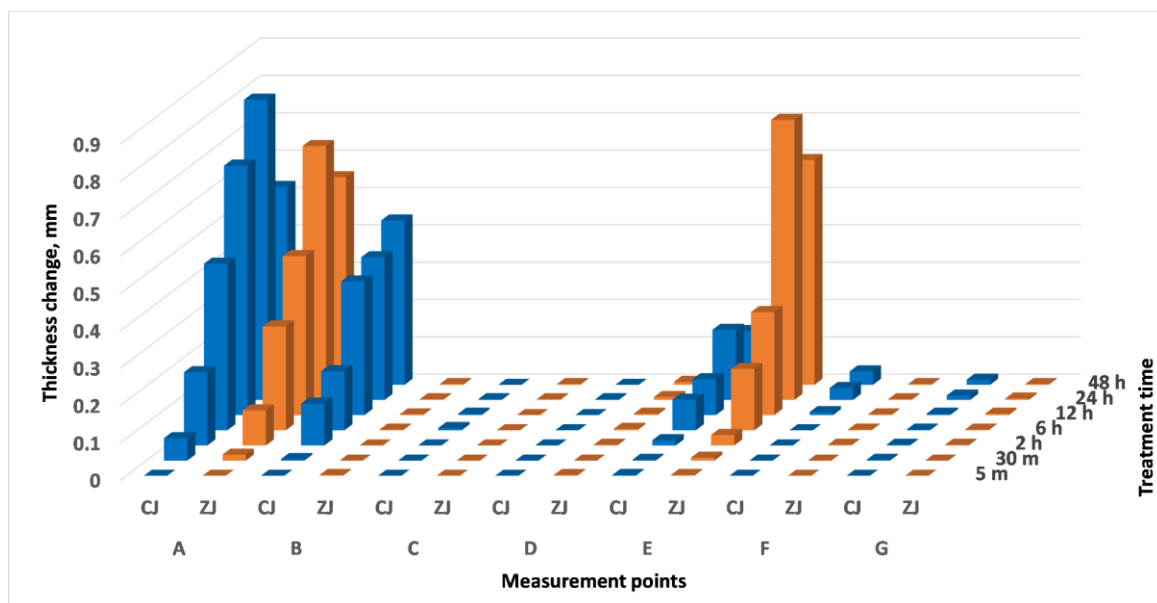


Figure 4. The average thickness swelling of specimens with conventional (CJ) and zero joints (ZJ) at the measurement points (A-G) after different moisture exposure times

Table 3 contains the average rating values of the measuring points in function of treatment time and joint type. The values confirm the statements related to Figure 4. The first differences in rating values (see Table 1) between conventional and zero joints appeared after 2 hours of exposure at the left corner, and after 12 hours both joints showed significant changes, the value decreased from 5 to 2. Rating differences between the two joint types were less accentuated at the opposite corner; however, zero joint values were worse than conventional joint values. In point B, the conventional joint degraded gradually, but the zero joints remained intact after 2 hours of exposure. This contradiction needs to be analysed further on a larger sample to discover if it is local gluing defects or the variation is too high.

Table 3. Classification of measuring points based on the assessment criteria

| Measuring points | Treatment duration |    |       |    |    |    |    |    |     |    |     |    |     |    |
|------------------|--------------------|----|-------|----|----|----|----|----|-----|----|-----|----|-----|----|
|                  | 5min               |    | 30min |    | 2h |    | 6h |    | 12h |    | 24h |    | 48h |    |
|                  | CJ                 | ZJ | CJ    | ZJ | CJ | ZJ | CJ | ZJ | CJ  | ZJ | CJ  | ZJ | CJ  | ZJ |
| A                | 5                  | 5  | 4     | 5  | 3  | 4  | 2  | 2  | 2   | 2  | 2   | 2  | 2   | 2  |
| B                | 5                  | 5  | 5     | 5  | 3  | 5  | 3  | 5  | 2   | 5  | 2   | 5  | 2   | 5  |
| C                | 5                  | 5  | 5     | 5  | 5  | 5  | 5  | 5  | 5   | 5  | 5   | 5  | 5   | 5  |
| D                | 5                  | 5  | 5     | 5  | 5  | 5  | 5  | 5  | 5   | 5  | 5   | 5  | 5   | 5  |
| E                | 5                  | 5  | 5     | 5  | 5  | 5  | 4  | 3  | 4   | 2  | 3   | 2  | 3   | 2  |
| F                | 5                  | 5  | 5     | 5  | 5  | 5  | 5  | 5  | 5   | 5  | 5   | 5  | 5   | 5  |
| G                | 5                  | 5  | 5     | 5  | 5  | 5  | 5  | 5  | 5   | 5  | 5   | 5  | 5   | 5  |

### 3.2 Steam resistance

Figure 5 displays the thickness swelling values of the edgebanded specimens exposed to steaming. The thickness increases were visible after each treatment cycle, reaching a maximum of 1.75 mm at the corner of one of the conventionally edgebanded specimens. After 5 minutes, the differences between the two joint types were noticeable, but after 10 minutes, this difference attained 40%. The corner was more affected by steaming than the edges; however, after 15 minutes of exposure the average thickness swelling of the conventional joint at a distance of 100 mm reached 1 mm. This value is 80% higher than the value of the zero joint (0.2 mm). The measured values demonstrate that the conventional joints are more sensitive to steaming.

Statistical evaluations revealed that thickness-swelling values were significantly higher at the corner than at a distance of 100 mm from the corner. No significant difference appeared between the conventional and zero joint after one cycle; however, after 10 and 15 minutes of steam exposure the zero joint swelling values were considerably lower (with 39% and 37%). A gradually increasing thickness swelling can be observed by extending the exposure time from 5 to 15 minutes. At 100 mm from the corner, there is a significant difference between the two joint types after 10 minutes treatment, and the conventional joint thickness increased considerably at the end of the total exposure. Figure 6 shows the effect of moisture and steam on the edgebanded samples.

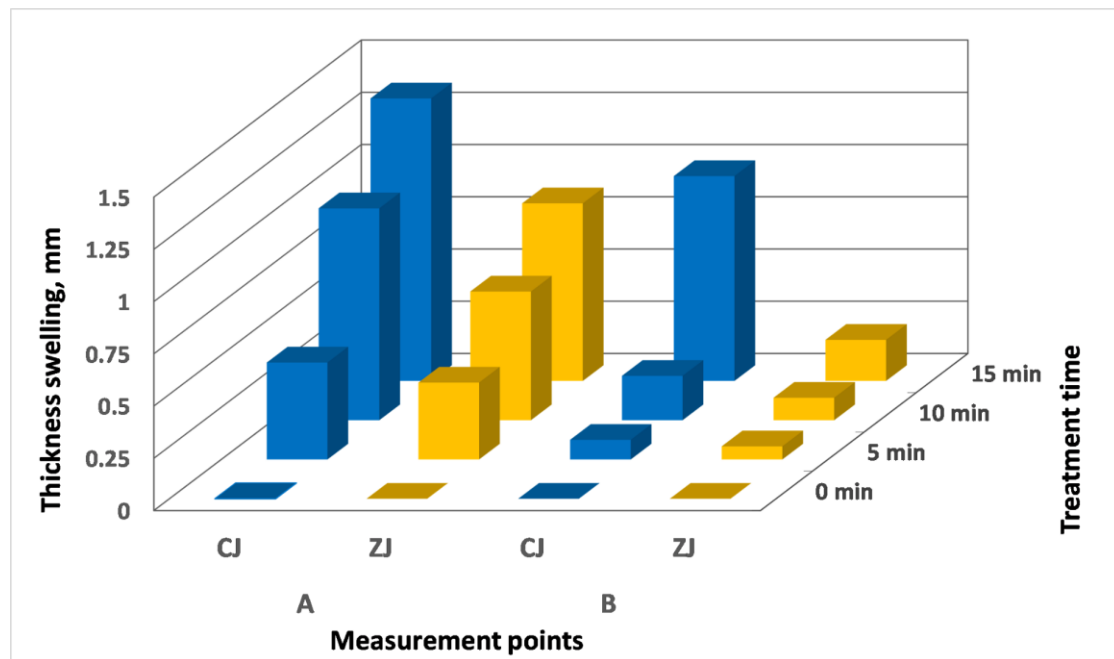


Figure 5. The average thickness swelling of specimens with conventional (CJ) and zero joints (ZJ), in the measurement points (A and B) after different steam exposure times

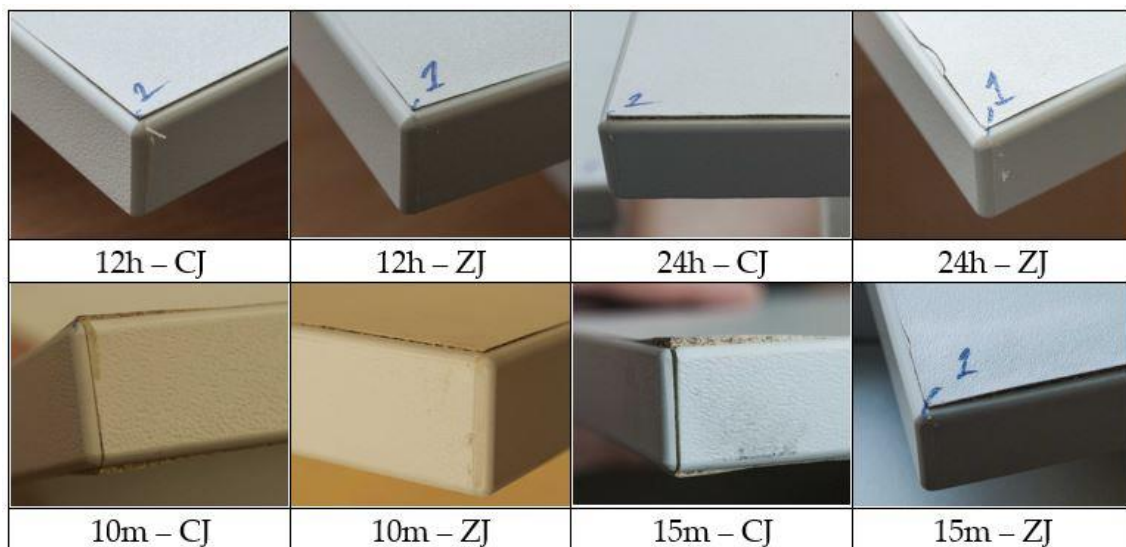


Figure 6. The effect of moisture and steam on the edgebanded samples

### 3.3 Environmental impacts

In Table 4, we collected the most important environmental inventory data, namely the inputs and outputs specific to the process. According to standard ISO 14044:2006 (ISO 2006b), the inputs could be product, material, or energy flow that enters a unit process. The output could be product, material or energy flow that leaves a unit process (products and materials include raw materials, intermediate products, co-products, and releases).

These inputs and outputs were the environmental factors (material and energy abstractions and emissions during the technology) that define the system boundaries of the analysis. The inputs and outputs were empirical data as well as data based on Hungarian manufacturing technology. These data were collected in the reference year 2016.

*Table 4. Total environmental inventory data of edgebanding technologies (our own data were collected from manufacturing technology in Hungary, reference period: 2016)*

| Environmental inventory                                     | Unit    | Edgebanding    |               |
|-------------------------------------------------------------|---------|----------------|---------------|
|                                                             |         | Conventional   | Zero-joint    |
| <i>Input</i>                                                |         |                |               |
| Acrylonitrile-Butadiene-Styrene (ABS) edge material         | kg      | 48.50          | 53.69         |
| Electrical energy                                           | kWh     | 171.68         | 246.59        |
| Treatment fluid (ethanol)                                   | ml      | 458.10         | 458.10        |
| Chipboard 18 mm                                             | kg (m³) | 2277.99 (3.50) | 2277.9 (3.50) |
| Ethylene-vinyl acetate copolymers, adhesive granulate (EVA) | kg      | 0.10           | –             |
| Lubricating oil                                             | kg      | 0.0016         | 0.0016        |
| Package of adhesive (plastic)                               | kg      | 0.002          | 0.002         |
| Package of edging material (cardboard)                      | kg      | 3.65           | 3.65          |
| <i>Output</i>                                               |         |                |               |
| Acrylonitrile-Butadiene-Styrene (ABS) edge material         | kg      | 35.42          | 39.84         |
| Treatment fluid (ethanol)                                   | ml      | 343.56         | 343.56        |
| Chipboard 18 mm                                             | kg (m³) | 2257.44 (3.47) | 2257.4 (3.47) |
| Ethylene-vinyl acetate copolymers, adhesive granulate (EVA) | kg      | 0.09           | –             |
| Packaging waste material                                    | kg      | 0.011          | –             |
| Edge material waste                                         | kg      | 13.08          | 13.85         |
| Chipboard waste                                             | kg (m³) | 20.55 (0.032)  | 20.55 (0.032) |
| Treatment fluid waste                                       | ml      | 114.54         | 114.54        |
| Package of adhesive (plastic)                               | kg      | 0.002          | 0.002         |
| Package of edging material (cardboard)                      | kg      | 3.65           | 3.65          |
| Waste oil (recycled)                                        | kg      | 0.0016         | 0.0016        |

Based on the environmental inventory data, costs emerging in the examined life cycle can also be included in the life cycle costing (LCC) method. LCC analysis provides an appropriate basis for calculating the costs in the life cycle. Through this, profit can be maximized at all stages of the life cycle. One of the advantages of LCC analysis is that all investment costs and cost structures can be demonstrated. This enables a more accurate calculation, which leads to better decision making (Laáb 2021).

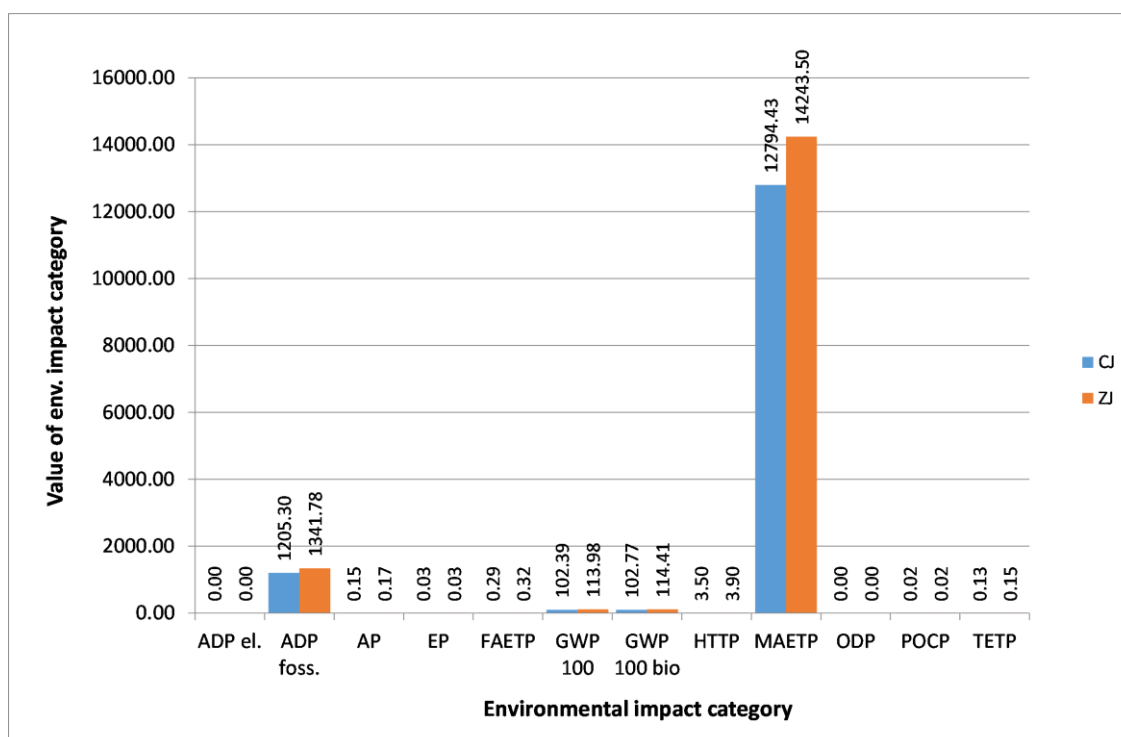
In the case of the environmental inventory data, we assigned the costs primarily to the inputs (the prices of the inputs come from the raw material distribution companies, July 2020 prices). According to this, the total cost of inputs for conventional edgebanding technology were HUF 792,896; while the total cost of inputs for the zero-joint edging technology were HUF 1,152,642. We can state that zero-joint technology displays a 1.45 times surplus compared to conventional technology. Both technologies showed considerable costs of the edging material, the chipboard, and the electrical energy. Concerning the input, significant differences (more than doubled value) occurred from the quantity of acrylonitrile-butadiene-styrene (ABS) edge material (in the case of 1006.98 m, traditional: HUF 213,480, zero-joint: HUF 568,950). The costs of ABS edge material waste by technologies were the following: traditional, HUF 57,574 (27%); zero-joint, HUF 146,768 (28%).

Differences in electricity consumption also arose. Zero-joint technology requires 1.44 times more energy input compared to conventional technology, which results in additional costs.

The usage of ethylene-vinyl acetate copolymers, adhesive granulate (EVA) in the conventional technology results in only HUF 226,300 extra cost compared to the zero-joint technology.

In the impact assessment process, the environmental impact categories of the specific production processes were analysed by technology according to the operational sequence of the edgebandings.

The following results in Figure 7 were based on the CML 2001 (version: April 2015) problem-oriented impact assessment method.



**Abbreviations: Conventional (CJ) and Zero joints (ZJ) edgebanding;**

ADP el. – Abiotic Depletion (ADP elements) [kg Sb-Equiv.]; ADP foss. – Abiotic Depletion (ADP fossil) [MJ]; AP – Acidification Potential (AP) [kg SO<sub>2</sub>-Equiv.]; EP – Eutrophication Potential (EP) [kg Phosphate-Equiv.]; FAETP – Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB-Equiv.]; GWP 100 – Global Warming Potential (GWP 100 years) [kg CO<sub>2</sub>-Equiv.]; GWP 100 bio – Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO<sub>2</sub>-Equiv.]; HTTP – Human Toxicity Potential (HTTP inf.) [kg DCB-Equiv.]; MAETP – Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB-Equiv.]; ODP – Ozone Layer Depletion Potential (ODP, steady state) [kg R11-Equiv.]; POCP – Photochem. Ozone Creation Potential (POCP) [kg Ethene-Equiv.]; TETP – Terrestrial Ecotoxicity Potential (TETP inf.) [kg DCB-Equiv.]

*Figure 7. Environmental impacts of edgebanding technologies in the impact categories of the CML 2001 (April 2015) impact assessment methodology*

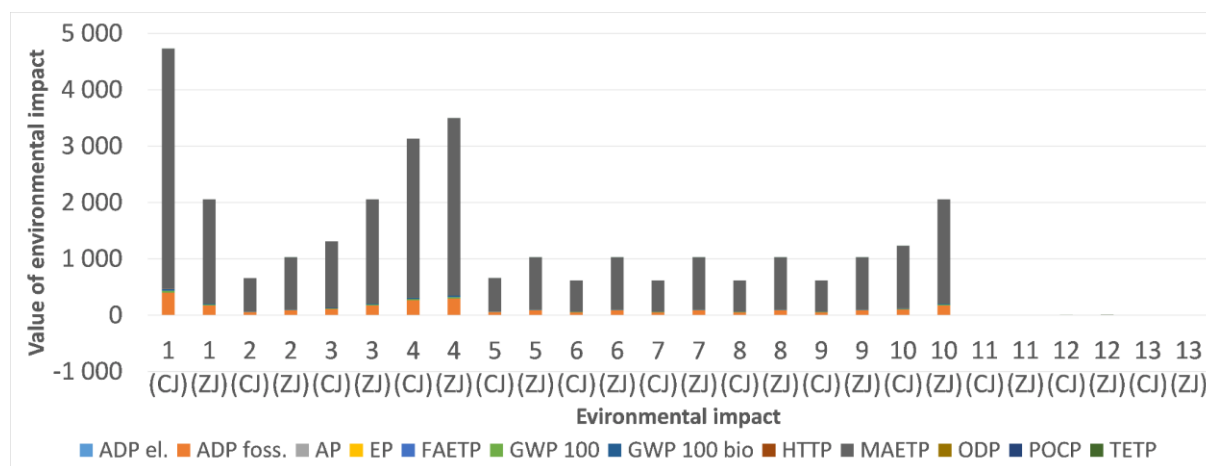
The technologies had the greatest impact on *Marine Aquatic Ecotoxicity Pot. (MAETP)* during their entire life cycle based on the CML 2001 (April 2015) problem-oriented (focusing on midpoints) assessment method. This can be explained by the edge material consumption of the technologies and by the transport. *ADP foss.-Abiotic Depletion (ADP fossil)* emerged as a significant impact category.

GWP 100-Global Warming Potential (GWP 100 years) values were negligible. *The life cycle contribution evolved in the proportion of 47% conventional – 53% zero-joint according to the impact categories.*

Figure 8 displays the contribution of the different operational steps within the conventional and zero-joint edgebanding technologies to the above environmental impact categories.

**Operational steps (conventional):** 1) Placing and feeding the edgebanding material roll into the machine + handling of the chipboard surfaces; 2) 1 mm milling of chipboard edge; 3) Melting, adding EVA granulate and applying glue + pressing the edgebanding onto the workpiece edge (bonds the edge banding to the substrate); 4) End-cutting banding material; 5) Trimming excess material at the bottom and top of edges; 6) Fine trimming excess material at the bottom and top of edges; 7) Rounding of edges; 8) Scraping any surplus of glue and banding materials; 9) Milling of workpiece on the edges; 10) Polishing of the edge surface + heating the edge of the workpiece for colour correction using hot air blower; 11) Lubricant oil; 12) Raw materials transport 1; 13) Raw materials transport 2

**Operational steps (zero-joint):** 1) Loading of banding material + handling of the chipboard surfaces with anti-adhesive fluid; 2) 1 mm milling of chipboard edge; 3) Pressing the edgebanding onto the workpiece edge (bonds the edge banding to the substrate); 4) End-cutting banding material; 5) Trimming excess material at the bottom and top of edges; 6) Fine trimming excess material at the bottom and top of edges; 7) Rounding of edges; 8) Scraping any surplus of banding materials; 9) Milling of workpiece on the edges; 10) Polishing of the edge surface + heating the edge of the workpiece for colour correction using hot air blower; 11) Lubricant oil; 12) Raw materials transport 1; 13) Raw materials transport 2



**Abbreviations:** Conventional (CJ) and Zero joints (ZJ) edgebanding;

ADP el. – Abiotic Depletion (ADP elements) [kg Sb-Equiv.]; **ADP foss.** – **Abiotic Depletion (ADP fossil) [MJ];** AP – Acidification Potential (AP) [kg SO<sub>2</sub>-Equiv.]; EP – Eutrophication Potential (EP) [kg Phosphate-Equiv.]; FAETP – Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB-Equiv.]; GWP 100 – Global Warming Potential (GWP 100 years) [kg CO<sub>2</sub>-Equiv.]; GWP 100 bio – Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO<sub>2</sub>-Equiv.]; HTTP – Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]; **MAETP – Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB-Equiv.];** ODP – Ozone Layer Depletion Potential (ODP, steady state) [kg R11-Equiv.]; POCP – Photochem. Ozone Creation Potential (POCP) [kg Ethene-Equiv.]; TETP – Terrestrial Ecotoxicity Potential (TETP inf.) [kg DCB-Equiv.]

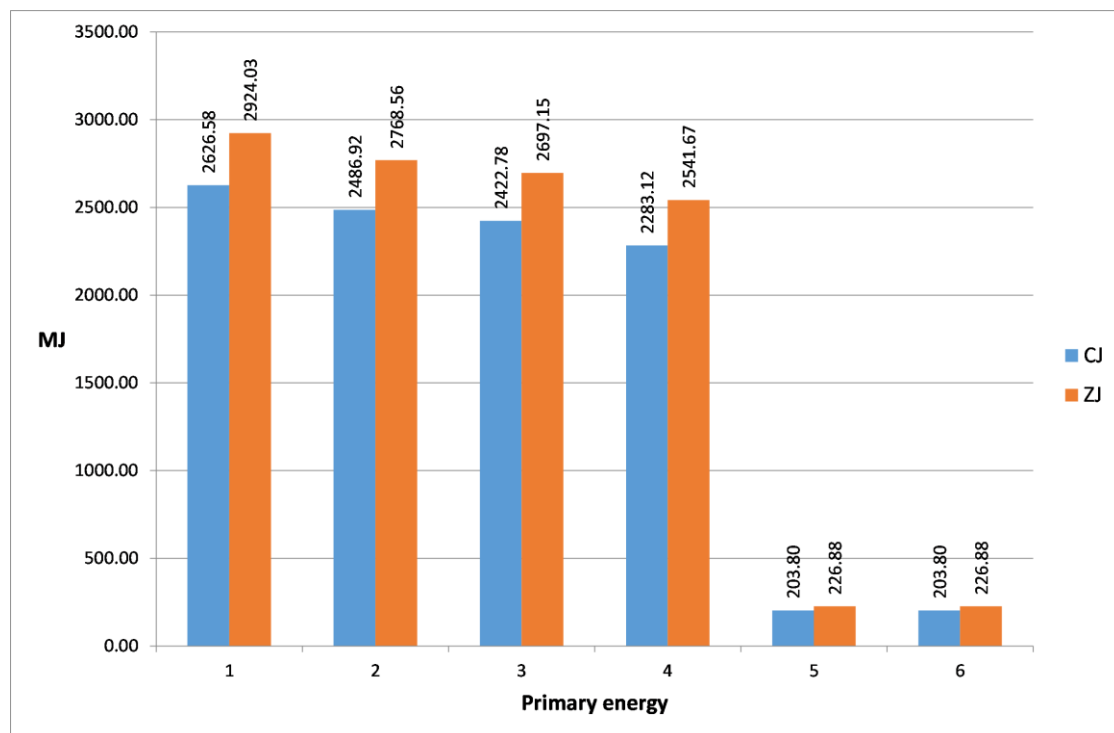
*Figure 8. Contribution to environmental impact categories of operational steps of conventional and zero-joint edgebanding according to impact categories of CML 2001 (April 2015) impact assessment methodology*

According to our examination (Figure 8), the following operational steps in the edgebanding technologies demonstrated considerable environmental impacts:

- Operational steps marked with the number 1. This is due to the electrical energy intake, meaning an extra energy demand compared to the other steps in the case of both alternatives. There is a strong indicator of this as regards the impact categories.
- Operational steps marked with the number 3. In the case of conventional technology, the step of “Melting, adding EVA granulate and applying glue + pressing the edgebanding onto the workpiece edge (bonds the edge banding to the substrate)” while in the zero-joint technology, the step of “Pressing the edgebanding onto the workpiece edge (bonds the edge banding to the substrate)” had higher energy demand compared to the others.
- Operational steps marked with the number 4. We have higher energy demand here in our model as well due to the extra energy demand of the compressor in addition to the energy demand of “End-cutting banding material” in both the conventional and the zero-joint technology.
- Operational steps marked with the number 10. In both alternatives, the extra energy demand of heat transfer of colour correction need to be counted.

Calculation of the primary energy demand of the technologies is a built-in module in the GaBi Professional LCA software as well. *Figure 9* illustrates the primary energy demand of the examined edging technologies. Life-cycle contribution rate developed as 47% conventional – 53% zero-joint according to the model of energy consumption.

The constructed life cycle models have the attribute that *the usage of the renewable energy sources (8.41%) is only a fraction of the non-renewable energy sources used in the manufacturing technologies*. This demonstrates a high potential of environmental development.



**Abbreviations:** Conventional (CJ) and Zero joints (ZJ) edgebanding;

1 – Primary energy demand from renewable, and non-renewable resources (gross cal. value) [MJ];

2 – Primary energy demand from renewable, and non-renewable resources (net cal. value) [MJ];

3 – Primary energy from non-renewable resources (gross cal. value) [MJ];

4 – Primary energy from non-renewable resources (net cal. value) [MJ];

5 – Primary energy from renewable resources (gross cal. value) [MJ];

6 – Primary energy from renewable resources (net cal. value) [MJ]

*Figure 9. Primer energy demand of edgebanding technologies [MJ]*

## 4 CONCLUSIONS

In our durability study, the edgebanded furniture fronts were the most sensible at the corners when exposed to moisture. Due to the high variations, the differences between conventional and zero joints were not statistically significant; however, there was a difference of two to three classes based on the assessment criteria for water resistance (Table 1). There was no consistency between the thickness swelling values of the two corners, since the conventional joints had higher values at the left corner. The edgebanded fronts exposed to moisture for a short period of time did not suffer significant deteriorations. In the case of steaming, the specimen's corners were affected the most and the thickness swelling of zero joints was significantly lower after the second and third treatment cycle. At 100 mm from the corners, the deterioration of edgebanding was considerably smaller and the visible differences between the joint types appeared after longer exposure.

The life cycle cost assessments revealed that zero-joint technology displays a 1.45 times surplus cost compared to conventional technology. Both technologies showed considerable costs of the edging material, the chipboard, and the electrical energy.

In our environmental study, we examined the environmental impact of edgebanding in woodwork by following the technological operation of a modern edgebander machine. In relation to conventional and the zero-joint edging technologies, according to all impact assessment methods, the life-cycle contribution rate was uniformly 47% *conventional* – 53% *zero-joint* by impact category. *The higher indicator values of zero-joint method are due to the larger edge material consumption and the higher energy demand.* The constructed life cycle models have the attribute that *the usage of the renewable energy sources (8.41%) is only a fraction of the non-renewable energy sources used in the manufacturing technologies.* This demonstrates a high potential of environmental development.

Zero-joint technology appears to avoid the application of hot melt adhesive, but replacing these does not necessarily result in better environmental indicators. Nevertheless, zero-joint edgebanding does not just improve the appearance from an aesthetic point of view (invisible gluing joint line on the panels), but also exceeds the conventional edgebanding technology when durability aspects are considered.

Of course, the results obtained by the LCA examinations also depend on the nature of the model constructed in the analysing program and on how the electrical energy demand is distributed among the specific operational steps.

Not only are zero-joint edges aesthetically pleasing, but they also provide stronger, longer-lasting edges and anti-bacterial benefits. The LCA method considers the environmental impact of the manufacturing technology, but it also addresses product durability. In the latter, the two technologies examined in this study demonstrated significant differences.

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## Using Different Approaches of Particle Size Analysis for Estimation of Water Retention Capacity of Soils: Example of Keszthely Mountains (Hungary)

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**Abstract** – PSD (particle size distribution) is a key factor affecting soil hydro-physical properties (e.g. hydraulic conductivity and water retention), which makes its determination essential. Climate change increases the importance of water retention and permeability as extreme weather events can severely impair the water supply of drought-sensitive vegetation. The amount of water in soils is expected to decrease. The modified Thornthwaite model considers soil properties such as root depth, topsoil layer thickness and particle size distribution (silt and clay fraction) of soil particles combined with the most significant soil properties. At the beginning of the research, we developed a laser diffraction method to replace the standard based “pipette” sedimentation method. The theoretical background of laser diffraction measurements is already known, but their practical application for estimating soil water retention capacity is still poorly understood. The pre-sieving of soil aggregates, the pre-treatment (disaggregation and dispersion) of the samples greatly influence the obtained results. In addition to the sedimentation method, laser diffraction measurements (Malvern Mastersizer 3000) were applied with three variants of pre-treatment. For comparison, the results of a Leptosol, a Cambisol, and a Luvisol were prepared for the first modified Thornthwaite water balance model. Significant differences appeared, especially during drought periods, which could be a basis for studying soil drought sensitivity. The development of our method can estimate the water retention capacity of soil, which could support adaptive forest management plans against climatic and pedological transformations.

### particle size analysis / pipette method / laser diffraction

**Kivonat – A talaj víztartó-képességének értékelése szemcseanalízissel Keszthelyi-hegységi talajokon.** A Soproni Egyetem Környezet- és Földtudományi Intézetében végzett jelen kutatás fő témája a talajok szemcseméret eloszlásának a vizsgálata, melynek több célja is van. Egyik kitűzött cél a laboratóriumban jelenleg használt hagyományos és időigényes „pipettás módszer” lecserélése a gyorsabb és modernebb lézerdiffrakciós mérési módszerre. A másik cél annak vizsgálata, hogy a talajokat miként befolyásolják a klímaváltozás hatására végbemenő változások, illetve a talajok vízfelvevő- és megtartó képessége hogyan hat az erdőállományok vitalitására. A jelen cikk a kezdeti lépéseket hivatott részletesebben bemutatni három különböző talajtípuson. Egyrészt összehasonlítjuk a pipettás módszer és három különböző módon előkezelt minta lézerdiffrakciós módszerrel mért mechanikai összetétel eredményeit, másrészt bemutatjuk a mérési eredményeken alapuló vízmérleg

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modell pontosítását, mely az analitikai módszerek gyakorlati alkalmazását és erdészeti jelentőségét is szemléleti.

**granulometria / pipettás módszer / lézerdiffrakció**

## 1 INTRODUCTION

The Russian pedologist Vasily Dokuchaev was the first to define soil-forming factors. He identified the five main factors, namely geological, climatic, biological, topographical, and soil age. The massive impact of human activities is considered the sixth factor today. Soil formation processes include humus formation, leaching, and clay formation, but the most basic formation process is weathering (Blaskó 2011). Soil can be characterized as primary mineral residues mixed with secondary minerals formed by weathering and fragmentation. Mineral particle sizes in the composition vary greatly depending on the quality of the minerals and their formation or mode of fragmentation.

Different soil-forming factors and processes cause different-sized soil particles. The particle size distribution (PSD), or the qualitative characteristic expressing this (soil texture), and the relative position of the particles of different sizes are among the most important soil indicators (Stefanovits 1971). This influences many soil properties, particularly the size of the interfaces between the soil phases (specific surface area) and, consequently, the major physical and chemical processes taking place on these surfaces. In addition to the soil structure, this also affects porosity, which, in turn, affects water retention and hydraulic conductivity (Bieganski et al. 2018). Soil porosity can be described by the total volume of soil pores and by pore size distribution. We can distinguish two main pore types: structural (inter-aggregate) and textural (intra-aggregate) pores (Beven – Germann 1982, Schlotter – Schack-Kirchner 2013). The pores can also be divided according to size, e.g. micropores, macropores, and other differentiated divisions (SSSA, 1997). Using the capillary tube model described by the Young-Laplace equation, the matric potential (water retention) can be related to effective pore diameter as follows: macropores:  $> 75 \mu\text{m}$ ,  $< 1.6 \text{ pF}$ ; mesopores:  $30\text{--}75 \mu\text{m}$ ,  $1.6\text{--}2 \text{ pF}$ ; micropores:  $5\text{--}30 \mu\text{m}$ ,  $2\text{--}2.78 \text{ pF}$ ; ultramicropores:  $0.1\text{--}5 \mu\text{m}$ ,  $2.78\text{--}4.47 \text{ pF}$  and cryptopores  $< 0.1 \mu\text{m}$ ,  $> 4.47 \text{ pF}$  (Rajkai et al. 2015).

Though sedimentation methods (sieve-pipette or hydrometer method) are the most commonly used methods to determine PSD, the use of laser diffraction methods (LDMs) is also presently widespread (di Stefano et al. 2010). The pipetting method is a classical sedimentation method in which a certain amount from the suspension is pipetted after the settling time has elapsed. The dried mass of the particle fractions is then measured (MSZ 08-0206, 1978). Calculations are completed according to the Stokes-law. Spherical grains are usually assigned with the density of quartz ( $\rho=2.65 \text{ g/cm}^3$ ). Although the particle shapes are not uniformly spherical, for calculation purposes they should be considered as such. Most silt and clay particles possess a plate or tubular structure rather than a spherical structure, so the direction of movement is perpendicular to the maximum cross-section. Thus, as the settling rate of the particle decreases, the expected *tensile strength* of the particle increases, denoting that the particle shapes affect the result (Polakowski et al. 2014).

Laser diffraction particle analysis is an efficient procedure because it takes significantly less time, covers larger size ranges, and requires a smaller amount of sample (Bieganski et al. 2018). The definition is based on the relationship between light and surface. Light impinges on the particle surface, allowing light to refract, bend, reflect, and absorb on the surface (according to *Lambert-Beer law*). Laser diffraction particle analysis is based on the fact that the particle reflects the light beam at a certain angle, and that this angle increases as the particle size decreases. The beam of monochromatic light passes through the suspended sample, and

the beam of curved light thereby generated enters the multi-element sensor. The most commonly used PSD calculation method also assumes that the particles are spherical, i.e., the diameter of a given particle is an optical sphere (Eshel et al. 2004).

Site factors determine the occurrence and distribution of each tree species. By field factors, we mean the totality of factors that affect the growth and health of plants. Climatic factors, hydrological conditions (amount of available water from the soil), and soil properties (genetic soil types, physical diversity, and crop layer thickness) significantly influence the classification of Hungarian forest sites. Furthermore, altitude, exposure, slope, and the role of bedrock must also be considered (Babos 1966).

Site changes have accelerated in recent decades. Experts have noticed a rapid change in hydrological conditions such as groundwater level subsidence (Csáki et al. 2018). Hydrological factors change relatively quickly, but for the time being, they are mostly local problems. Climate is also a rapidly changing factor, but this change already affects the entire domestic forest population. Extreme changes in precipitation and temperature averages significantly impact the forest ecosystem and often leads to contiguous periods of drought. We can also expect climatic condition changes and soil transformation, both of which are expected to accelerate in the future due to temperature fluctuations. Two important changes in soils are directly related to climate change; an increase in soil temperature, which precipitates a decrease in soil moisture content; and altered soil moisture contents, which influences evapotranspiration and the rate of groundwater formation (Bidló – Horváth 2018).

Based on the research conducted at the University of Sopron in recent years, the spatial shift of certain climatic categories can be predicted (Führer et al. 2011, Führer 2018). In the future, the appearance of site type variants that have not occurred in Hungary must also be expected (Czímber – Gálos 2016, Mátyás et al. 2018). In order to prepare for the projected changes, the four forest climate categories used thus far had to be extended by a fifth, the so-called steppe climate category. In addition, the spatial shift of climate is accompanied by the emergence of soil types, whose formation conditions are related to other climates, plants, e.g. forest steppe. Applying planned forest management in advance of the new site type variants is crucial (Bidló – Horváth 2018).

Climate sensitive tree species and tree stand types should characterize classes of production site typology in forestry practice. Precisely measured meteorological parameters can determine climate classes (Beech, Hornbeam-oak, Sessile oak - Turkey oak, and Forest-steppe climates). Models indicate that forest climate classes will shift by the middle of the 21<sup>st</sup> century; forest-steppe climate class areas will increase, while closed forests are expected to decrease (Führer et al. 2017). The importance of individual soil properties will increase due to climate change. Concerning groundwater retention capacity, only forests with access to adequate water supplies will be able to survive longer rainfall-free periods. This ability is mainly determined by the physical soil variety and the thickness of the topsoil layer. Therefore, conducting the widest possible PSD measurements is vital to the health of our soils and forests.

The complex excavations performed in Hungary revealed that the effects of unfavourable soil properties, such as the physical variety or aggregates of coarse sand, are further aggravated by long dry and warm periods, which have been typical recently. For these reasons, the water holding capacity of our soils will become one of the most important production factors in the changing climate. The analysis of temperature and precipitation time series for a given area is suitable for detecting the effects of dry and warm periods in recent periods. The frequency of these is expected to increase in the future, especially in extreme weather situations, as well as the importance of microclimate conditions, in which exposure and forest structure will play key roles. Although weather is the primary cause of individual deforestation, soil conditions also play a very important role, as the water holding capacity of extremely shallow and shallow soils is exceedingly poor. As precipitation events have become more intense but less frequent in the

recent period, only a small portion of the precipitation that falls in this way can be stored in the soil. For this reason, we can expect that no water that can be taken up by the vegetation will remain in the soil during long dry periods between heavy rains. By predicting the expected negative effects, we can already conclude to what extent drought can aggravate the given unfavorable soil properties. Due to the long dry periods already mentioned, the declining amount of water in the soil causes so-called drought stress.

Significant deforestation occurred in the Keszthely Mountains in 2012. The devastation continued in subsequent years and appears to be ongoing even today. The destruction mainly affected the planted black pine stands, but the health of other tree species has also deteriorated. Primary studies have detected biotic pests as a damage cause, but also indicate that abiotic factors are the main causes of the destruction. Since the damage affected black pine, which has been present in the area for several decades (centuries), questions concerning abiotic factor changes arose. A chief goal of our work is to detect the changes and facilitate a solution. At the same time, questions concerning future possibilities also arise. Expected future changes may render currently reversible damage irreversible, which in turn prompts concerns about adapting to expected future site conditions as well as which tree species to use. This current paper presents the first steps of an analytical methodology development, which provides a basis for a more accurate estimation of the water retention capacity of soils. The final aim of this research is to help afforestation. More specifically, to aid climate-resistant tree species selection on a precise amount of silt and clay particle determination. The main questions of the current study are the following:

1. How can the time-consuming pipette method be efficiently replaced with a timesaving measuring instrument based LDM PSD? Furthermore, what are the advantages and disadvantages of LDM?
2. Do instrumental measurement results have better accuracy? Are those results optional for the water balance model?

## 2 MATERIALS AND METHODS

### 2.1 Durability study

Based on the previously stated objectives, we selected the Keszthely Mountains as the study area. The bedrock here is mainly dolomite. The soils of these mountains are very diverse, which makes them particularly suitable for our measurements. Due to the geological and topographical features of the area, the forests of the Keszthely Mountains have no access to surplus water, which means that the vegetation is dependent on precipitation. Most of the mountainous and hilly areas here are not under intensive land use and no upcoming land use changes are expected. Leaking wetlands in the loess areas and valleys, where oxygen-rich water moves under the cover or in the soil almost parallel to the surface, may exist to a small extent. The amount varies, but excess water is always beneficial for the local populations (Bidló et al. 2015).

In the sampling area, three soil profiles with different structures were selected to examine the organic matter content influencing the measurement in as varied a manner as possible (*Figure 1*). The topsoil layer thickness of black rendzina (BRE) is 30 cm, of which the reduced thickness is only 10 cm, which can be defined as shallow. The humus form of the soil is mull-humus. The topsoil contains organic plant residuals parts. The parent material is dolomite. Soil pH was 7.5 and was determined according to the Hungarian Standard (MSZ-08-0205/2-1978). The field capacity and the permanent wilting point of the topsoil layer was also significant. This layer has a loam texture with a crumbly structure, containing highly humus-rich rock fragments, richly networked by roots.



Figure 1. Location of the examined soil profiles in Hungary with the elevation information and the pictures of the investigated soil types

The topsoil layer thickness of brown earth (BEARTH) is 40 cm, of which the reduced thickness is also 40 cm, which can be defined as middle deep. The humus form of the soil is mull-humus. The parent material is loess (deposited on dolomite). Soil pH was 7.6. The texture was loam. Water conditions were favourable, water permeability was medium, and water-holding capacity was suitable. Nutrient supply was adequate. The supply of nitrogen, phosphorus, and potassium in the non-eroded section were also appropriate.

The topsoil layer thickness of lessivated brown forest soil (LBFS) is 100 cm, of which the reduced thickness is 100 cm, which can be defined as deep. The humus form of the soil is mull-humus. The parent material is loess. Soil pH was 5.8–7.9, slightly acidic in the topsoil, and the pH increased with soil depth (effect of loess). The texture was sandy loam. A typical three-layered soil. The water management of such soils was excellent, the water permeability is medium, and the water field capacity is adequate. The water storage capacity increased by the fact that the B horizon has a weak water retention effect.

## 2.2 Analytical methods

### *Standard based pipette sedimentation method (PSM)*

The samples for both procedures were prepared according to a modified version of the Hungarian Standard (MSZ-08-0206, 1978). After weighing the soil sample, the organic matter was removed with hydrogen peroxide until the soil turned grey and the humus materials decomposed into water and carbon dioxide (the original standard does not suggest to destroy the organic matter). Then Na-pyrophosphate solution was added to the sample as dispersing agent and shaken for 6 hours. The soil suspension was then washed through a 0.2 mm mesh sieve into a large porcelain bowl using warm distilled water and a rubber brush. This process should be repeated until the water that drips off is transparent. The coarse sand fraction remaining on the sieve was washed into a small porcelain dish of known weight without loss

using distilled water. The suspension of silt and clay passed through a 0.2 mm sieve was washed into a 1000 ml settler, then filled with distilled water and pipetted out from the given depth after given time.

#### *Laser diffraction method (LDM)*

Since three types of treatment were conducted, a more detailed description of these follows. The previously mentioned Malvern Mastersizer 3000 particle analyser was used for the laser diffraction particle size analysis. The device itself consists of a laser light source, light processing optics, a cell, a lens, and a multi-element detector. The multi-element detector provides the diffraction pattern. A data processing unit is also needed for the deconvolution of the diffraction data, as well as for volumetric particle size distribution, related data processing, and reporting (Malvern 2013). The optical unit is the center of the system, designed to transmit red laser light and blue light through the sample. The light is transmitted to a detector, which generates data from light scattering caused by particles in the sample. The measuring cell functions as an interface between the dispersion unit and the optical unit. Wet dispersion units are designed to circulate a liquid sample through the measuring cell. Measuring range: 0.01  $\mu\text{m}$  – 3500  $\mu\text{m}$ . The measurement is quite simple: a Hydro EV dispersion unit is placed in a 1000 ml beaker, filled with 800 ml of distilled water, and a soil sample is added to the distilled water accompanied by ultrasound. Ultrasound prevented settling to the bottom of the beaker for heavier aggregates and prevented re-agglomeration in the samples. The blue light ( $\lambda=470$  nm) was used to capture the background, while the red light ( $\lambda=632.8$  nm) was used to detect particles. The rotation speed was 2750 rpm and Mie theory was applied, refraction index 1.52 and absorption index 0.1 for the dispersed phase, and refraction index of 1.33 for water as the dispersing phase.

The treatments used were as follows for instrumental measurement:

- **M1** = Sample containing organic matter: In the case of the soil samples, the organic matter content was not destroyed; only the soil was suspended and the solution was homogenized. The prepared sample was added from the shake flask to the dispersing unit.
- **M2** =  $\text{NaPO}_3$  dispersed sample, pre-treated with hydrogen peroxide ( $\text{H}_2\text{O}_2$ ): The second treatment is the same as the preparation for the pipette method. Adhesives in the soil include humus, iron and alumina oxides and hydroxides, and calcium carbonates ( $\text{CaCO}_3$ ).  $\text{H}_2\text{O}_2$  treatment is used to destroy humic substances, while diluted hydrochloric acid (HCl) should be used to remove  $\text{CaCO}_3$ .  $\text{NaPO}_3$  was used for dispersion. Complexing agents are used to form iron and aluminium oxides (oxide hydroxides). To prevent re-coagulation of the particles, a peptizing agent (NaOH and Na brine, in rare cases Li brine) is added to the soil sample and soil suspension.
- **M3** = Sample pre-treated with hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) and hydrochloric acid: In the third preparation, we only destroyed the soil organic matter content. The humic substances are destroyed with hydrogen peroxide, while diluted hydrochloric acid is used to remove the calcium carbonate.

The PSD measurement results of the pipette method, considered as a standard, were compared with the LDM results obtained with different treatments using SPSS statistical software package to find the best reliable (best correlated) LDM procedure.

### **2.3 Water balance model calculations**

To detect drought stress, the Thornthwaite water balance model (Thornthwaite – Mather 1955) was used, which, in addition to monthly temperature and precipitation data, also includes soil

physical diversity, rooting depth, available water (EW) and maximum water uptake (EW<sub>m</sub>) (1). Monthly precipitation was reduced by an interception to determine the annual drought stress index (Is) (2). Granier et al. (1999) assumed stress when the relative recoverable moisture content (REW) of the soil drops below 40%. In the case of long-term drought period, this percentage could be higher in Hungary. Model parameters: monthly temperature and precipitation, reduced topsoil layer thickness, and root depth. Furthermore, the relative extractable water amount was refined with the data of the measured silt and clay fractions of the soils. At this point, we used the PSD results previously measured by different analytical methods. The models were prepared in MS Excel program.

$$\text{REW} = \text{EW} / \text{EW}_m \quad (1)$$

$$\text{Is} = \sum \text{SWD} / \text{EW}_m \quad (2)$$

$$\text{SWD} = \text{EW}_m \cdot 0.4 - \text{EW} \quad (3)$$

Where:

REW: the relative extractable water content  
 EW: the available water volume  
 EW<sub>m</sub>: the maximum of water absorption  
 Is: the annual drought stress index  
 SWD: the water deficit stored in the soil.

### 3 RESULTS AND DISCUSSION

#### 3.1 Particle size distribution

All measurement results were compared during the evaluation. The focus was on the correlation between the results of pipette (PSM) and laser diffraction (LDM) particle analysis. Moreover, the connection between the three data groups measured with the instrument was considered as well. In comparing the results, the different fractions were compared separately using correlation diagrams for conclusions. *Table 1* summarizes the sums of silt% and clay%.

*Table 1. Results of the silt+clay fraction (%) determined with PSM and LDM*

| Soil type | Depth<br>(cm) | S+C %<br>(Pi) | S+C %<br>(M1) | S+C %<br>(M2) | S+C %<br>(M3) |
|-----------|---------------|---------------|---------------|---------------|---------------|
| LBFS      | 0 – 5         | 25            | 20            | 12            | 40            |
| LBFS      | 5 – 25        | 27            | 36            | 54            | 17            |
| LBFS      | 25 – 60       | 35            | 40            | 62            | 33            |
| LBFS      | 60 – 100      | 27            | 36            | 60            | 27            |
| LBFS      | 100 – 120     | 11            | 29            | 48            | 43            |
| BRE       | 0 – 15        | 39            | 13            | 33            | 56            |
| BRE       | 15 – 30       | 17            | 13            | 32            | 8             |
| BEARTH    | 0 – 10        | 49            | 24            | 69            | 60            |
| BEARTH    | 10 – 40       | 43            | 25            | 31            | 63            |

S+C %: summarized value of Silt%+ Clay%; Pi: Pipette measurement; M1: Sample containing organic matter; M2: Dispersed sample treated with Hydrogen-peroxide (H<sub>2</sub>O<sub>2</sub>); M3: Sample treated with hydrogen-peroxide (H<sub>2</sub>O<sub>2</sub>) and hydrochloric acid; LBFS: lessivated brown forest soil; BRE: Black rendzina; BEARTH: Brown earth

Differently measured clay and silt fractions were compared. The clay content is interesting because it is the best efficiency indicator of the preparation methods (Kun et al. 2013, Yang et

al. 2015, Makó et al. 2017). The clay + silt fraction is one of the most fundamental input soil parameters of water balance models. For clay content, the 2  $\mu\text{m}$  clay/silt fraction boundary (Figure 2) and the 7  $\mu\text{m}$  clay/silt fraction boundary (Figure 3) were determined (Makó et al. 2019). In addition, only filtered values were entered into the program, with “obscuration” greater than 25 and “residual” results greater than 2.5 selected. Two statistical numbers were considered for the samples, the Coefficient of Determination ( $R^2$ ) and the Root Mean Square Error (RMSE). The RMSE number shows both an underestimation and overestimation of the results, while  $R^2$  value means a close or weak correlation between the pipette and the laser methods. Figures clearly indicated that the extent of RMSE varied depending on pre-treatments and fraction boundaries. The smallest underestimation or overestimation was measured for untreated suspensions by choosing the 7  $\mu\text{m}$  fraction limit. The samples without pre-treatment had the highest  $R^2$ , while the lowest  $R^2$  values were obtained for the only destroyed samples, for both limits. The highest RMSE value was observed for the destroyed and dispersed samples at the 7  $\mu\text{m}$  clay boundary. Considering all the pre-treatments, it can be said that the  $R^2$  values were slightly higher for the 7  $\mu\text{m}$  fraction limit, while for the 2  $\mu\text{m}$  fraction limit we found a smaller underestimation or overestimation on average.

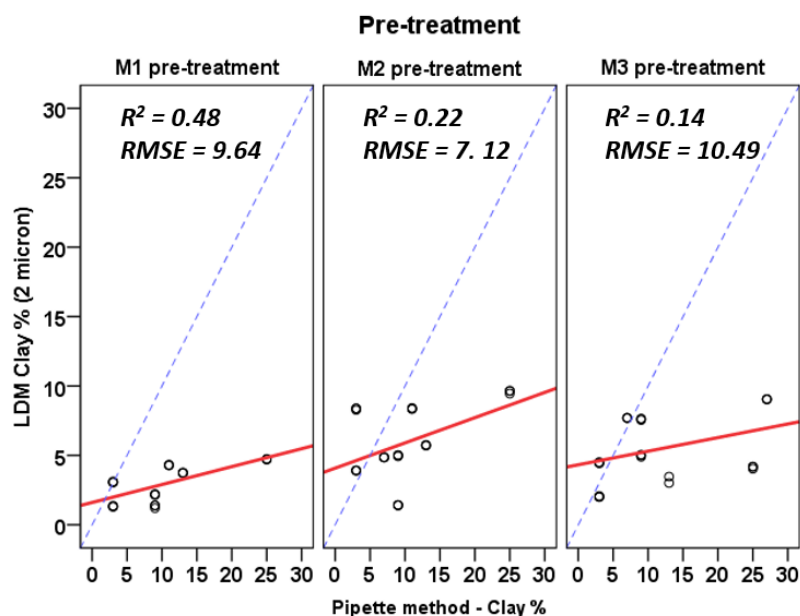


Figure 2. Comparison of clay content at 2  $\mu\text{m}$  fraction limit determined with pipette and laser diffraction method

The 2 and 7 micron limits do not require separate evaluation for this fraction, as their sums are the same. On Figure 4, values marked in brown represent samples with high organic matter content from the upper horizons. The values show a low regression at first glance and a rather large overestimation. The only acceptable value ( $R^2 = 0.41$ ) is shown for M3 due to the high soil organic matter (SOM) content of each sample. However, the confounding effect of SOM did not appear in this sample because if we take out the data marked in brown, we still obtain a good regression fit. In the case of the M1 sample, the data with a high organic matter content stand out from the other values. There are two possible reasons for this. It is possible that some of the clay + silt content remained in the form of aggregates and that the incorporation of ultrasound did not help to separate the aggregates. Another possibility is that the undestroyed organic debris, which remained in the suspension, hindered the laser measurement. The coexistence of these two options interfered with the poor regression relationship ( $R^2 = 0.08$ ). If

the data marked in brown are taken out of the analysis, a high regression line is obtained ( $R^2 = 0.94$ ).

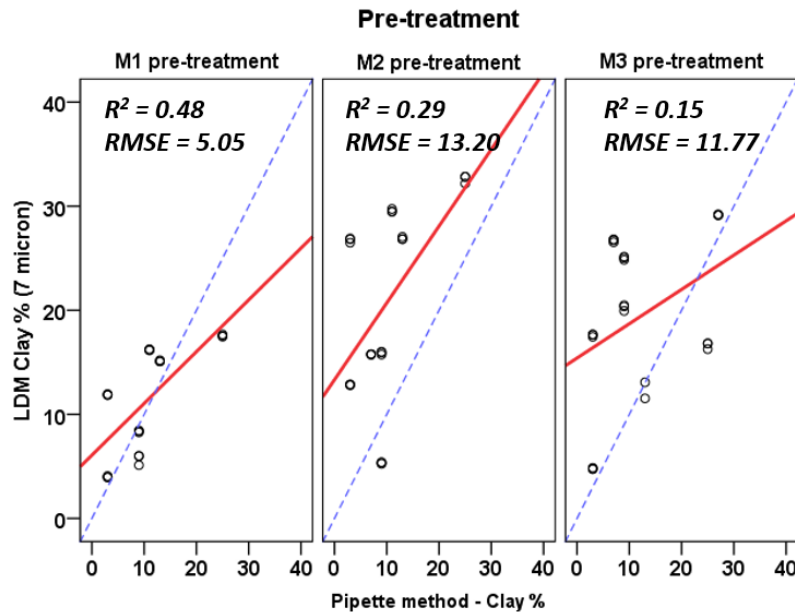


Figure 3. Comparison of clay content at 7  $\mu\text{m}$  fraction limit determined with pipette and laser diffraction method

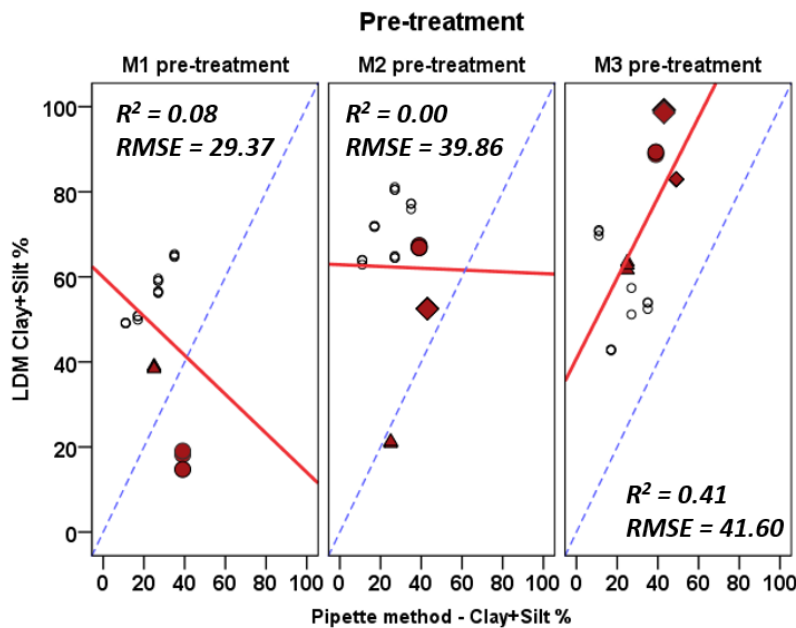


Figure 4. Comparison of three type of instrumental measurement

The destroyed and dispersed (M2) sample displays the same behaviour (Figure 4). The value of  $R^2$  ( $= 0.00$ ) is weak as well, but if we take these high organic matter contents out of the evaluation, we get a better fit ( $R^2 = 0.42$ ). To conclude, the clay + silt content always overestimates the pipette clay + silt content in laser diffraction measurements. In the cases of M1 and M2, this occurred even without the samples with high SOM content, and in the case of M3, it even occurred in the samples with high SOM content. Promisingly, Igaz and colleagues (2020) performed PSM and LDM comparisons on 542 soil samples and found that a

polynomial-based regression model is adequate for obtaining an approximation of the pipette method and laser tools (Malvern Mastersizer 2000, Fritsch Analysette22) after recalculation of the data.

For practical applicability, the obtained results were used to construct the Thornthwaite monthly water balance model. To prepare the water scales, we first used the pipette measurements followed by the values obtained with the laser instrument. Following the measurements, water scales for the three studied soil types were prepared to investigate the relationships between the soil particle properties and the water retention capacity. Water balance diagrams were prepared using the properties of the soils and the climatic conditions of the area (Gálos et al. 2017, Bidló et al. 2019). It is important to note that below a certain limit, plants cannot absorb enough water and water stress develops.

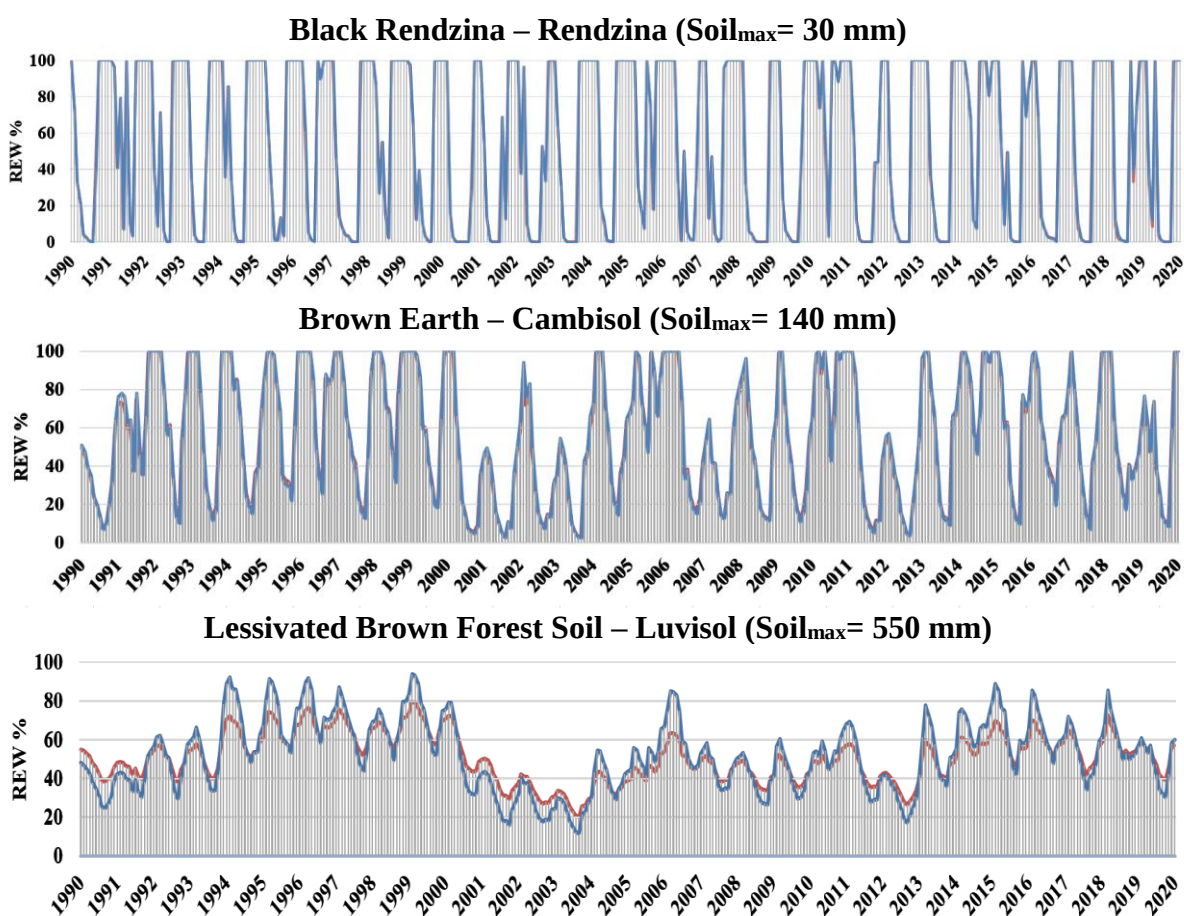


Figure 5. Water balance models derived from results of pipette (red line) and M2 laser diffraction measurements (blue line) ( $Soil_{max}$ : maximum amount of water that can be stored for an emptied soil during a precipitation event, REW%: relative extractable water amount)

Figure 5 displays the comparison of the Pipette method (blue colour) and M2 (red colour) measurements made by the similar pre-treatment.

In the case of LBFS, the water was well retained and evaporated slowly during the drought periods, of which there were three (1990-1993; 2000-2003; 2011-2013). These conditions ensured continuous forest cover. Mention should also be made of the amount of water stored in the soil, which is 500 mm, and the thickness of the reduced topsoil is 100 cm.

BEARTH absorbs water relatively quickly, but it releases it just as quickly due to the physical variety of the soil. The maximum amount of water that can be stored in the soil is 100 mm, which is already significantly less than LBFS. During drought periods, this soil type was

already much less able to store enough water for vegetation. The figure also clearly shows the difference in years with very high rainfall (e.g. 2010), when plants were relieved from water stress.

For the BRE soil type, Figure 5 illustrates that the soil saturates quickly, but also loses water content quickly, especially during drought periods. The maximum amount of water that can be stored is small (30 mm) due to the shallow (15 cm) thickness of the crop layer, which, however, has an exceptionally high organic matter content. The water retention capacity of the soil is no longer enough to maintain closed forests.

The three different figures clearly show that LBFS with a deep topsoil layer thickness is much more sensitive to water loss during drought periods. The measurement differences are mainly visible in the LBFS water balance, especially in drought years when the instrument over-measures. After 2-3 years of drought, the Mastersizer measurements underestimate, and then the difference in measurements decreases in the following years. Therefore, analytical studies require further investigation to draw further conclusions.

## 4 CONCLUSIONS

Determining the particle size distribution of soils helps to monitor the hydro-physical properties of the soil (e.g. hydraulic conductivity or water retention). Climate change increases the importance of water retention and permeability as extreme weather events can severely impair the water supply of drought-sensitive vegetation. Overall, the amount of water is expected to decrease in the future.

As a first step of this research, we developed the laser diffraction method, which is a faster and more reliable pre-treatment measurement method than the classical “pipette” sedimentation method. The theoretical background of laser diffraction measurements is well known, but their practical application for estimating soil water retention is still poorly understood. (Yudina et al. 2020). The modified Thornthwaite model considers soil properties (e.g. root depth, topsoil layer thickness) and particle size distribution (silt and clay fraction). In addition to the sedimentation method, laser diffraction measurements (Malvern Mastersizer 3000) were conducted with three variants of pre-treatment.

- The pre-sieving and pre-treatment of the samples greatly influence the obtained results. Weak regression lines and high underestimations are possible due to sources of error from pre-treatments.

*Explanation:* During organic matter decomposition, it is likely that not only the humus content decomposed. The undegraded organic debris from the topsoil in the samples may have remained in large quantities. The aggregates and the mineral phase may also have been destroyed by removing organic materials and carbonates, which may have resulted in the decomposition and transformation of some of the clay minerals.

- For laser diffraction measurements, sampling from the suspension can also be a source of error, as a significant part of the sand fraction presumably settles down, which means the suspension could not be dispersed evenly.

*Explanation:* This can be seen in the determination of the clay + silt content when overestimating the samples. Another possible source of error is that the soil suspension could not be completely washed out. After decomposition, dissolved, possibly semi-decomposed, organic substances such as hydrogen peroxide may have formed, which may have formed a precipitate with the dispersant during sonication. Therefore, the correlation between pipette and laser diffraction measurements may be weak.

- Based on our results, the particle size distribution has great importance in determining the water retention capacity of soils. We obtained lower-than-expected correlation

values for the particle size distribution determined in different ways, which could be due to several reasons (Yang et al. 2015, Bieganski et al. 2018).

*Explanation:* One such reason is that the laser diffraction instrument gives a volume percentage, while pipetting measurements give weight percentages. The density of soil particles greatly influences pipette measurements. This parameter is negligible with laser diffraction measurement. However, in the latter case, the refractive index of the particles can be a significant factor.

The current study indicates that laser diffraction measurement can replace the classical sedimentation (pipette) method in the near future. These facts are sufficient to obtain different results. In addition, the removal of organic matter also worsened the correlation of the results. For comparison, the results of a Leptosol, a Cambisol, and a Luvisol were prepared for the first modified Thornthwaite water balance model. Significant differences appeared, especially during drought periods, which could provide a basis for studying the drought sensitivity of soils. The development of our method allows for the estimation of the water retention capacity of soil, which could help forest management in planning adaptations to climatic and pedological changes.

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## Growing of Black Locust (*Robinia pseudoacacia* L.) Candidate Cultivars on Arid Sandy Site

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**Abstract** – In the late 1990s, Hungarian Forest Research Institute researchers produced 15 micropropagated black locust (*Robinia pseudoacacia* L.) clones as part of a program to select clones that could be successfully grown on arid sites. Five of these clones (R.p. 'Vacsi', R.p. 'Szálás', R.p. 'Oszlopos', R.p. 'Homoki' and R.p. 'Bácska') have been categorized as cultivar candidates. The current study presents information concerning the 'Bácska', 'Vacsi' and 'Homoki' candidate cultivars. Based on research results obtained thus far, the three aforementioned candidate cultivars seem the most promising. The cultivars, aged 6-15 years, were tested in a variety comparison trial under arid, sandy soil conditions in the Danube–Tisza Interfluvium near the town of Helvécia. Significant differences ( $p < 0.05$ ) were observed during results evaluation of full inventories and during the comparison of candidate cultivars partly with common black locust and partly with 'Jászkiséri' cultivars. The 15-year-old 'Homoki' outperformed common black locust in diameter and mean tree volume; 'Vacsi' outperformed in stem quality. The 14-year-old 'Bácska' candidate cultivar was compared with the 'Jászkiséri' cultivar and the 'Oszlopos' cultivar candidate. 'Bácska' proved to be significantly better in diameter and mean tree volume than 'Jászkiséri', but weaker in trunk quality. The South Korean National Institute of Forest Science has supported this research for several years. The growing technology of the mentioned candidate cultivars are also examined in Korea, taking local ecological conditions into account.

***Robinia pseudoacacia* / micropropagation / selection / black locust growing**

**Kivonat** – Akácfajtajelöltek termesztése szárazodó homoki termőhelyen. Az 1990-es évek végén az Erdészeti Tudományos Intézet kutatói a szárazodó termőhelyeken is eredményesen termesztendő akácklónok szelektálását célul kitűző program keretében 15 klónt állítottak elő, amelyből öt (R.p. 'Vacsi', R.p. 'Szálás', R.p. 'Oszlopos', R.p. 'Homoki' és R.p. 'Bácska') fajtajelölti minősítést kapott. Jelen tanulmányban, a fentebb említett fajtajelöltek közül, a 'Bácska', a 'Vacsi' és a 'Homoki' kerülnek bemutatásra. Az eddigi vizsgálati eredmények alapján ez a három fajtajelölt tűnik a legígéretesebbnek. A fajtajelölteket a Duna–Tisza közti homokhátságon (Helvécia település közelében), szárazodó, gyenge homoki termőhelyen létesült fajta összehasonlító kísérletben vizsgáltuk 6-15 éves korban. Az állomány-felvételek eredményeinek kiértékelése, a fajtajelölteknek részben a közönséges akáccal, részben a 'Jászkiséri' akáccal történő összehasonlítása során szignifikáns különbségeket tapasztaltunk. A 15 éves 'Homoki' átmérő, és átlagfa-térfogat, a 'Vacsi' törzsmínőség tekintetében múlta felül a közönséges akácot. A 'Bácska' fajtajelöltet a 'Jászkiséri' fajttal, valamint az 'Oszlopos' fajtajelölttel hasonlítottuk

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össze, ahol a 14 éves 'Bácska' átmérőben és átlagfa-térfogatban szignifikánsan jobbnak, törzsminőségben viszont gyengébbnek bizonyult a 'Jászkisérinél'.

Ezt a kutatómunkát több éve támogatja a Dél-Koreai Erdészettudományi Intézet, ahol az említett fajtajelöltek termesztési technológiai tulajdonságait szintén vizsgálják az ottani ökológiai feltételek figyelembevételével.

***Robinia pseudoacacia* / mikroszaporítás / szelekció / akáctermesztés**

## 1 INTRODUCTION

Black locust (*Robinia pseudoacacia* L.), a hard broadleaved tree species, originates from North America. The estimated area of black locust plantations beyond the native range is approx. 3 million ha globally (Schneck 2010). The fast spread of black locust can be expected in two continents in the future: Asia, primarily in the countries of China and South Korea; and Europe, with Hungary, Romania, Poland and some Mediterranean countries (mostly Bulgaria, Italy, France, Turkey) being the most prominent black locust growers (Li et al. 2014, Nicolescu 2020).

Black locust was introduced to Europe more than 400 years ago (Demené – Merzeau 2007). In Hungary, the first records of black locust introduction date back to the 18th century. Since then, black locust area has been steadily increasing (Vadas 1911, Keresztesi 1988). Currently the species covers approx. 24% of forested area in Hungary (HCSO 2019). Black locust was introduced to South Korea in the 19<sup>th</sup> century. After the Korean War in the 1960s, it was heavily used in the reforestation of denuded mountains. Recently, black locust is one of the most extensively established exotic tree species in Hungary and South Korea. Its widespread growth can be attributed to its drought tolerance, frequent and abundant seed production, rapid growth, relatively high tree yielding potential, good honey production, excellent vegetative regeneration ability, and low susceptibility to pest and pathogens. Its role in soil protection (erosion and deflation control) is also decisive. Black locust wood is durable, high quality, and is utilized for many purposes (Keresztesi 1988, Lee et al. 2004, Noh et al. 2010, Rédei 2013, Lee et al. 2019, Nicolescu et al. 2020). In addition to its many advantageous properties, its ability to propagate aggressively and its inability to associate due to its high light demand and strong root competition should not be overlooked (Vítková et al. 2015, 2017). Furthermore, common black locust may also possess negative tree characteristics to varying degrees. These include warped and space-curved trunks as well as forking and low industrial wood yields, all of which are disadvantageous for growing (Keresztesi 1988).

Hungarian Forest Research Institute (FRI) staff have been improving black locust growing technology for decades, including the creation and introduction of selected black locust cultivars, the primary goal of which is to improve stem quality as well as increase yield and nectar production. Thanks to this research work, we have several black locust cultivars and candidate cultivars available for use in industrial plantations (Keresztesi 1983, 1988; Rédei et al. 2001, 2002, 2008, 2017).

In the late 1990s, FRI researchers produced 15 micropropagated clones as part of a research programme to select clones that could be successfully grown on arid sites. Five of these (*Robinia pseudoacacia* 'Vacsí', *Robinia pseudoacacia* 'Szálás', *Robinia pseudoacacia* 'Oszlopos', *Robinia pseudoacacia* 'Homoki' and *Robinia pseudoacacia* 'Bácska') have been granted a provisionally approved cultivar candidate category by the Hungarian National Food Chain Safety Office (Rédei et al. 2002, 2006, 2008, 2013a, 2013b).

Apart from Hungary, several countries have initiated research programmes that aim to improve black locust wood quality and/or increase biomass production for energy purposes. Black locust breeding and improvement is undertaken in the USA (Bongarten et al. 1991,

Straker et al. 2015), Germany (Lieseback et al. 2004, Böhm et al. 2011), Poland (Szyp-Borowska et al. 2016), Bulgaria (Kalmukov 2005, 2014), Greece (Dini-Papanastasi – Panetsos 2000), Turkey (Dengiz et al. 2010), India (Sharma et al. 2006), China (Dunlun et al. 1995, Li et al. 2021), and South Korea (Lee et al. 2007). Countries are increasingly interested in black locust improvement and management, with special attention focused on the species' response to climate change impacts.

The main goals of this paper are as follows:

- providing a brief review of the international aspects of black locust propagation and improvement,
- documenting available knowledge about black locust candidate cultivars,
- presenting the most important results of growing black locust within the Hungarian-South Korean cooperation as a reference work.

## 2 ORIGIN AND BOTANICAL DESCRIPTION OF THE BLACK LOCUST CANDIDATE CULTIVARS

The black locust improvement (selection) programme launched in 1996 has two aims: to help quality development of black locust propagation material and to complete the variety choice of particular regions producing new black locust cultivars that can be grown effectively under unfavourably changed ecological conditions. The following are the main selection step processes: choice of black locust population containing trees of good phenotype; choice of plus trees; seed collection from the plus trees; seedling production, establishing a collection with the progenies of the plus trees; organizing a collection of seedlings selected from the progenies; clonal selection from the seedlings' collection by tissue culture (micropropagation) method; initiating clone trials for selecting the best clones. The programme has improved 15 new black locust clones (Rédei 2013). As mentioned above, five of these clones have recently been designated as candidate cultivars.

The following segment presents the botanical description of R. p. 'Homoki', R. p. 'Bácska', R. p. 'Váci' and R. p. 'Oszlopos' (R. p. 'Szálás' is not subject of this paper).

### 2.1 Bácska (*Robinia pseudoacacia* 'Bácska')

The breeding label for Bácska is KH 56A 2/5, which indicates the origin of the clone (KH means Kéleshalom). Bácska has medium density foliage, with 11-17 leaflets per leaf stalk. In most cases the leaflet is orderly elliptical possibly inversely egg-shaped, of which the tip is rounded or indented without any splinter. The length of spines ranges from 6 to 12 mm. The base is small, possibly medium-sized, and evenly acuminate toward its point. The shoot is ribbed and uniformly salad-green. It develops many, relatively short shoots (not determining features, these depend mostly on the environment). The rod of 'Bácska' is strongly ribbed and spines, which subtend 90° with the rod, cover its full length. These decrease evenly in size toward the apical part. Generally, 21 to 24 nodes are situated along the length of the 50 cm part of shoot. The bark is smooth and steel-grey in colour. The flower is white. The flowering-axis is green with medium-length. The flower cluster is loose; a cluster consists of 23-31 pieces of flowers. The calyx is green with brown pigmentation, but green-toned determinatively. After flowering, the colour changes to brownish-red. Bácska's flowering intensity was average at Kecskemét-Méheslapos in 2006 and in 2007. Its flowering began three days later than and lasted two days longer than the common black locust at Gödöllő (Osváth-Bujtás – Rédei 2007).

## 2.2 Homoki (*Robinia pseudoacacia* 'Homoki')

The breeding label for this cultivar is MB 17D  $\frac{3}{4}$ , which indicates the origin of the clone (MB means Mikebuda). 'Homoki' makes a dense foliage impression. The compound, which consists of 13-19 leaflets, is of an average length. Mid-positioned leaves are the largest ones. The leaflet is drawn; sometimes it is orderly elliptical-shaped of which the form factor is 3-3.5. The tip of the leaflet is mildly indented and lacks splinter. The spines are small, bodkin-like, and 5-8 mm in length. 'Homoki' black locust shoots are reddish, greenish-brown and are typically ribbed. Rods are strongly ribbed with a medium number of nodums (15-21). Tiny spines subtend at an acute angle (approx. 30°) with the rod. The bark is greyish-brown, with lenticels of scattered position emerging from the surface. Often longitudinal brown stripes can be seen on sapling bark. The flowering-axis is dull green with purple discoloration. The petals are white with mild greenish-yellow colour in the middle of the vexil. 'Homoki' began flowering at average time at Kecskemét-Méheslapos in 2006 but lasted 2-4 days longer than the common black locust at Gödöllő. Its flowering was abundant in 2006 and in 2007 (Osváth-Bujtás – Rédei 2007).

## 2.3 Vacsi (*Robinia pseudoacacia* 'Vacsi')

This clone is labelled as PV 201E2/1, which indicates the origin (PV means Pusztavacs). 'Vacsi' develops olive-green, relatively sparse foliage after leafing. On average, there are 15-21 leaflets per leaf stalk. With the exception of the lowest leaflets, the mostly egg-shaped leaflets are identical in size. The form factor is 2.5-3. The leaf tips are rounded or indented and are ordered in an opposite leaf arrangement. Spines are mouse ear-like and small. Shoots are green, greenish-brown, and ribbed only on 5-15 cm of length on the youngest segments. The next part of shoot is cylindrical. The rod is covered by medium strong ribs, with an average number of nodums (19-21). Tiny spines are situated only on the lower part of the shoot. The bark of 'Vacsi' black locust is dark grey with scattered lenticels. It has white flowers and the flowering-axis is green. The calyx is light green and occasionally displays pink pigment; the petals are white with an olive-green spot. Flowering intensity was average at Kecskemét-Méheslapos in 2006 and was weak-medium in 2007 (Osváth-Bujtás – Rédei 2007).

## 2.4 Oszlopos (*Robinia pseudoacacia* 'Oszlopos')

The breeding label for this clone is PV 233A/1. It develops medium green rich foliage after vernal leafing. The compound leaf consists of 15-19 leaflets. The leaflet is elongated elliptical (its form factor is 3-3.5) with an acuminate tip, sometimes with splinter. The leaf base of leaflets is wedge-shaped. The 1-3 mm-long spines are situated on the underside of the rod. Their shape is uncharacteristic and nondescript. Shoots are light green, ribbed along 15-20 cm of length, while the other part of the shoot is cylindrical. Medium strong ribs, with many (27-30) nodums and little spines, cover the rods. Spines do not or hardly develop on the apical – longer – part of the rod and occur only along the lower 15-20 cm. The bark is greenish-grey with scattered lenticels. Flowering intensity was average at Kecskemét-Méheslapos in 2006 and in 2007. The same applies to flower quantity (Osváth-Bujtás – Rédei 2007).

## 2.5 Experiences of clone trials

The Hungarian Forest Research Institute has three clone trials (Helvécia, Kecskemét and Hajdúhadház) where 'Bácska' and 'Homoki' candidate cultivars proved to be the best (Rédei et al. 2013a, 2013b).

### 3 MATERIALS AND METHODS

#### 3.1 Site and stand parameters

Data used in this study emanated from black locust clone trials established in the forest subcompartment Helvécia 22 E (two experimental plots) in Danube–Tisza Interfluve, “Homokhátság” (sandy ridge) region (Figure 1). In the past three decades, the mean annual precipitation at the site was 574 mm while the mean annual temperature was 11.4 °C (Tölgyesi et al. 2016). The FOA has recognized this region as an increasingly arid zone in its long-term forecast. The most pessimistic assessments predict the risk of desertification (UNCCD 2006).

The experimental plots are located in a forest-steppe climate. The soil is slightly humous, sandy, and free-draining (according to the Hungarian forest site classification by Járó, 1972). The black locust stands at the site ranged from 6 to 15 years.

In experimental plot 1, we compared ‘Vacsi’, ‘Homoki’ candidate cultivars and the common black locust (control). The examined trees were 15 years old at the time (January 2021) of the full inventory (Laar – Akca 2007).

In experimental plot 2, ‘Jászkeséri’ cultivar and ‘Bácska’ and ‘Oszlopos’ candidate cultivars were compared. These were 14-year-old trees.

In the experimental plots, 30 stems/clone were examined.

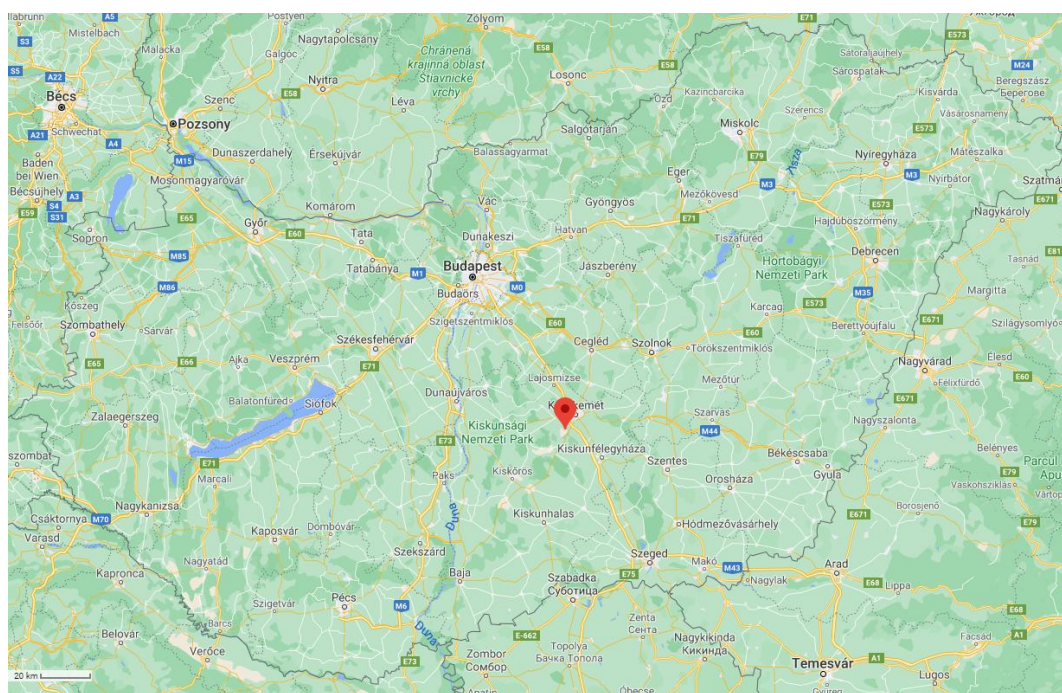


Figure 1. Location of the research site (Helvécia)

The location (forest subcompartment) and the most important dendrometric characteristics, including age, mean height (H), mean diameter at breast height (DBH), mean tree volume (v) and stem form value (SFV), extended by data from previous full inventories (6-year-old and 7-year-old trees) are compiled in Table 1. The stem volume was calculated using the following volume function based on the volume table for black locust (Sopp – Kolozs 2013):

$$v = 10^{-8} \cdot d^2 \cdot h^1 \cdot (h/[h-1.3])^2 \cdot (-0.6326 \cdot d \cdot h + 20.23 \cdot d + 3034), \quad (1)$$

where v is stem volume (m<sup>3</sup>), d is diameter at breast height (cm), h is tree height (m). The mean tree volume (v, m<sup>3</sup>/tree) was calculated using the means of stem volume for each of the

experimental plots. The following classifications were used for the evaluation of stem form value (SFV): 1 – stem form is straight, 2 – more or less straight, 3 – crooked, 4 – very crooked.

*Table 1. Parameters of black locust candidate cultivars, 'Jászkiséri' cultivar, and common black locust (control) at 6-15 years old*

| Clones              | Experimental plot | Age (yr) | H <sub>m</sub> (m) | DBH (cm) | v (m <sup>3</sup> ) | SFV  |
|---------------------|-------------------|----------|--------------------|----------|---------------------|------|
| Homoki              | 1                 | 7        | 8.7                | 6.2      | 0.0227              | 1.78 |
| Vacsi               | 1                 | 7        | 7.8                | 5.3      | 0.0147              | 1.36 |
| Common black locust | 1                 | 7        | 6.36               | 3.86     | 0.0081              | 2.45 |
| Homoki              | 1                 | 15       | 10.5               | 9.8      | 0.0626              | 2.32 |
| Vacsi               | 1                 | 15       | 9.0                | 7.7      | 0.0327              | 1.66 |
| Common black locust | 1                 | 15       | 9.77               | 7.56     | 0.0343              | 2.37 |
| Bácska              | 2                 | 6        | 7.1                | 6.3      | 0.0131              | 1.74 |
| Oszlopos            | 2                 | 6        | 3.9                | 3.5      | 0.0034              | 2.23 |
| Jászkiséri          | 2                 | 6        | 6.28               | 5.81     | 0.0105              | 1.68 |
| Bácska              | 2                 | 14       | 11.4               | 11.2     | 0.0790              | 2.50 |
| Oszlopos            | 2                 | 14       | 6.7                | 7.6      | 0.0312              | 2.32 |
| Jászkiséri          | 2                 | 14       | 11.66              | 9.85     | 0.0616              | 1.96 |

Note: PV 233 A/1 ('Oszlopos') candidate cultivars are situated on the poorest spot of the site

### 3.2 Statistical analysis

Microsoft Excel 2016 and IBM SPSS Statistics 25 software packages were used for the statistical analysis of experimental results. Candidate cultivars were compared using one-way ANOVA and Fisher's least significance difference (LSD) test ( $p < 0.05$ ).

## 4 RESULTS AND DISCUSSION

Figure 2 presents the distribution of the candidate cultivars in the site index curves of the black locust yield table. As the figure shows, at 6 and 7 years old, the candidate cultivars (except 'Oszlopos' – PV 233A/1) belong to yield class I to III, and to yield class IV to VI at 14 and 15 years old.

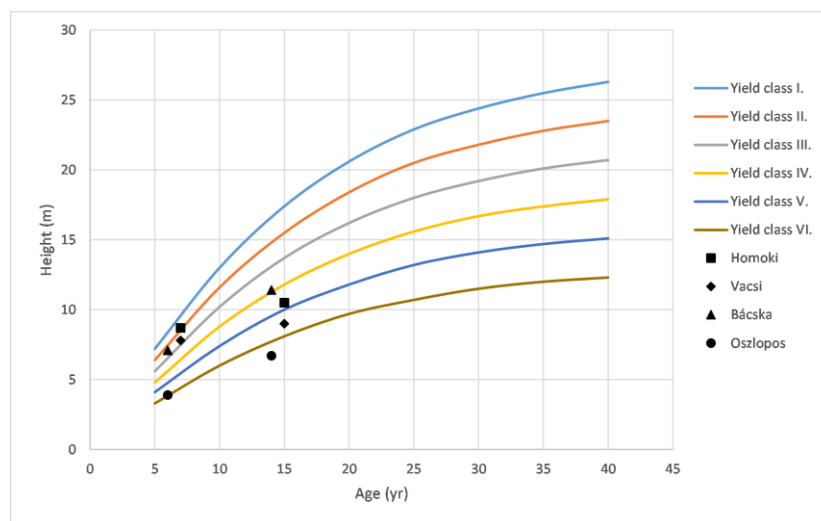


*Figure 2. 6-15-year-old black locust candidate cultivars in the site index curves of black locust yield table (based on Rédei 1984)*

In this study, significant ( $p < 0.05$ ) differences were observed between the examined candidate cultivars. More specifically, 15-year-old 'Homoki' outperformed the common black locust in diameter and mean tree volume; 'Vacsi' outperformed in stem quality (Table 2). The 14-year-old 'Bácska' cultivar candidate was compared with the 'Jászkiséri' cultivar and 'Oszlopos' cultivar candidate where 'Bácska' proved to be significantly better in diameter and mean tree volume, but weaker in stem quality than 'Jászkiséri' (Table 3).

Table 2. The result of one-way ANOVA (Helvécia 22 E/1)

|          |         |                 |            |        |             | 95% Confidence Interval |         |
|----------|---------|-----------------|------------|--------|-------------|-------------------------|---------|
| Clone    |         | Mean Difference | Std. Error | Sig.   | Lower Bound | Upper Bound             |         |
| DBH (cm) | Control | Homoki          | -2.2785*   | 0.5463 | 0.000       | -3.3611                 | -1.1959 |
|          |         | Vacsi           | -0.1372    | 0.5037 | 0.786       | -1.1353                 | 0.8609  |
|          | Homoki  | Control         | 2.2785*    | 0.5463 | 0.000       | 1.1959                  | 3.3611  |
|          |         | Vacsi           | 2.1413*    | 0.4848 | 0.000       | 1.1806                  | 3.1021  |
|          | Vacsi   | Control         | 0.1372     | 0.5037 | 0.786       | -0.8609                 | 1.1353  |
|          |         | Homoki          | -2.1413*   | 0.4848 | 0.000       | -3.1021                 | -1.1806 |

Based on observed means.

The error term is Mean Square (Error) = 4.757

|            |         |         |          |        |       |         |         |
|------------|---------|---------|----------|--------|-------|---------|---------|
| Height (m) | Control | Homoki  | -0.7480  | 0.4746 | 0.118 | -1.6886 | 0.1925  |
|            |         | Vacsi   | 0.7267   | 0.4376 | 0.100 | -0.1404 | 1.5938  |
|            | Homoki  | Control | 0.7480   | 0.4746 | 0.118 | -0.1925 | 1.6886  |
|            |         | Vacsi   | 1.4747*  | 0.4212 | 0.001 | 0.6401  | 2.3093  |
|            | Vacsi   | Control | -0.7267  | 0.4376 | 0.100 | -1.5938 | 0.1404  |
|            |         | Homoki  | -1.4747* | 0.4212 | 0.001 | -2.3093 | -0.6401 |

Based on observed means.

The error term is Mean Square(Error) = 3.590

|                                    |         |         |          |        |       |         |         |
|------------------------------------|---------|---------|----------|--------|-------|---------|---------|
| Mean tree volume (m <sup>3</sup> ) | Control | Homoki  | -0.0282* | 0.0066 | 0.000 | -0.0413 | -0.0151 |
|                                    |         | Vacsi   | 0.0017   | 0.0061 | 0.785 | -0.0104 | 0.0137  |
|                                    | Homoki  | Control | 0.0282*  | 0.0066 | 0.000 | 0.0151  | 0.0413  |
|                                    |         | Vacsi   | 0.0299*  | 0.0059 | 0.000 | 0.0183  | 0.0415  |
|                                    | Vacsi   | Control | -0.0017  | 0.0061 | 0.785 | -0.0137 | 0.0104  |
|                                    |         | Homoki  | -0.0299* | 0.0059 | 0.000 | -0.0415 | -0.0183 |

Based on observed means.

The error term is Mean Square(Error) = 0.001

|                 |         |         |          |        |       |         |         |
|-----------------|---------|---------|----------|--------|-------|---------|---------|
| Stem form value | Control | Homoki  | 0.0431   | 0.1419 | 0.762 | -0.2381 | 0.3243  |
|                 |         | Vacsi   | 0.7067*  | 0.1308 | 0.000 | 0.4474  | 0.9659  |
|                 | Homoki  | Control | -0.0431  | 0.1419 | 0.762 | -0.3243 | 0.2381  |
|                 |         | Vacsi   | 0.6635*  | 0.1259 | 0.000 | 0.4140  | 0.9131  |
|                 | Vacsi   | Control | -0.7067* | 0.1308 | 0.000 | -0.9659 | -0.4474 |
|                 |         | Homoki  | -0.6635* | 0.1259 | 0.000 | -0.9131 | -0.4140 |

Based on observed means.

The error term is Mean Square(Error) = 0.321

\*. The mean difference is significant at the 0.05 level

Table 3. The result of one-way ANOVA (Helvécia 22 E/2)

|             |            |            |            |            |       | 95% Confidence Interval |         |
|-------------|------------|------------|------------|------------|-------|-------------------------|---------|
|             |            |            | Mean       |            |       | Lower                   | Upper   |
| Clone       |            |            | Difference | Std. Error | Sig.  | Bound                   | Bound   |
| DBH<br>(cm) | Bácska     | Jászkiséri | 1.3181*    | 0.5360     | 0.015 | 0.2567                  | 2.3795  |
|             |            | Oszlopos   | 3.5695*    | 0.5581     | 0.000 | 2.4642                  | 4.6747  |
|             | Jászkiséri | Bácska     | -1.3181*   | 0.5360     | 0.015 | -2.3795                 | -0.2567 |
|             |            | Oszlopos   | 2.2514*    | 0.5360     | 0.000 | 1.1900                  | 3.3127  |
|             | Oszlopos   | Bácska     | -3.5695*   | 0.5581     | 0.000 | -4.6747                 | -2.4642 |
|             |            | Jászkiséri | -2.2514*   | 0.5360     | 0.000 | -3.3127                 | -1.1900 |

Based on observed means.

The error term is Mean Square(Error) = 5.919

|            |            |            |          |        |       |         |         |
|------------|------------|------------|----------|--------|-------|---------|---------|
| Height (m) | Bácska     | Jászkiséri | -0.2203  | 0.3351 | 0.512 | -0.8839 | 0.4433  |
|            |            | Oszlopos   | 4.7763*  | 0.3489 | 0.000 | 4.0853  | 5.4673  |
|            | Jászkiséri | Bácska     | 0.2203   | 0.3351 | 0.512 | -0.4433 | 0.8839  |
|            |            | Oszlopos   | 4.9966*  | 0.3351 | 0.000 | 4.3331  | 5.6602  |
|            | Oszlopos   | Bácska     | -4.7763* | 0.3489 | 0.000 | -5.4673 | -4.0853 |
|            |            | Jászkiséri | -4.9966* | 0.3351 | 0.000 | -5.6602 | -4.3331 |

Based on observed means.

The error term is Mean Square(Error) = 2.313

|                                    |            |            |          |        |       |         |         |
|------------------------------------|------------|------------|----------|--------|-------|---------|---------|
| Mean tree volume (m <sup>3</sup> ) | Bácska     | Jászkiséri | 0.0174*  | 0.0073 | 0.018 | 0.0030  | 0.0317  |
|                                    |            | Oszlopos   | 0.0479*  | 0.0076 | 0.000 | 0.0329  | 0.0628  |
|                                    | Jászkiséri | Bácska     | -0.0174* | 0.0073 | 0.018 | -0.0317 | -0.0030 |
|                                    |            | Oszlopos   | 0.0305*  | 0.0073 | 0.000 | 0.0161  | 0.0448  |
|                                    | Oszlopos   | Bácska     | -0.0479* | 0.0076 | 0.000 | -0.0628 | -0.0329 |
|                                    |            | Jászkiséri | -0.0305* | 0.0073 | 0.000 | -0.0448 | -0.0161 |

Based on observed means.

The error term is Mean Square(Error) = 0.001

|                 |            |            |          |        |       |         |         |
|-----------------|------------|------------|----------|--------|-------|---------|---------|
| Stem form value | Bácska     | Jászkiséri | 0.5444*  | 0.1210 | 0.000 | 0.3047  | 0.7842  |
|                 |            | Oszlopos   | 0.1842   | 0.1260 | 0.147 | -0.0654 | 0.4338  |
|                 | Jászkiséri | Bácska     | -0.5444* | 0.1210 | 0.000 | -0.7842 | -0.3047 |
|                 |            | Oszlopos   | -0.3602* | 0.1210 | 0.004 | -0.5999 | -0.1205 |
|                 | Oszlopos   | Bácska     | -0.1842  | 0.1260 | 0.147 | -0.4338 | 0.0654  |
|                 |            | Jászkiséri | 0.3602*  | 0.1210 | 0.004 | 0.1205  | 0.5999  |

Based on observed means.

The error term is Mean Square(Error) = 0.302

\*. The mean difference is significant at the 0.05 level

## 5 CONCLUSIONS

This study compared black locust candidate cultivars with common black locust and 'Jászkiséri' cultivars. After the evaluation of statistical analysis (one-way ANOVA) of experimental results, the present study found significant differences ( $p < 0.05$ ) between the

candidate cultivars and common black locust or 'Jászkiséri' locust. More specifically, 15-year-old 'Homoki' and 14-year-old 'Bácska' proved to be the best in diameter at breast height (9.8 cm and 11.2 cm) and mean tree volume (0.0626 m<sup>3</sup> and 0.0790 m<sup>3</sup>).

The evaluation of the experiment addresses the important fact of whether it is worthwhile to grow selected black locust cultivars and candidate cultivars on marginal sites. Detailed economic studies are needed to determine this, especially with regard to the expected added value (stem quality) of the candidate cultivars.

The Hungarian Forest Research Institute and the South Korean National Institute of Forest Science have been cooperating on the improvement of black locust cultivation in Hungary and South Korea for over ten years. The South Korean National Institute of Forest Science fully supports the project. Candidate cultivars evaluated in this manuscript are also available in South Korea and have been experimentally vegetative propagated and placed in variety comparison trials in recent years. The focus of our study was to investigate the growth relationships of the candidate cultivars on marginal sites, as the potential for future black locust propagation in such sites is under primary consideration in South Korea.

The systematic evaluation of the cultivation experiments and the selection of black locust clones and candidate cultivars to be proposed for public cultivation should be further extended to the following main fields:

- better definition of their site (ecological) requirements;
- development of a large-scale, profitable technology for their vegetative propagation (from root cuttings);
- further data collection and evaluation of the cultivation technological factors (planting spacing, mixing, cutting age, etc.) which are not yet sufficiently understood;
- extension of productivity (yield) studies, development of new yield models for groups of candidate cultivars;
- continued monitoring and evaluation of the resistance of candidate cultivars to biotic and abiotic pests;
- more consistent use of landscape ecology in species selection.

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