

Effects of CO₂ Laser Cutting Parameters on Kerf Width in Native Wood Species

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Kerf width variations in native wood species were evaluated with respect to CO₂ laser cutting, focusing on the impact of different laser parameters. By systematically varying power output and cutting speed on beech, oak, and spruce wood, the resulting kerf widths were quantified at the top and bottom of the cuts. Measurements were conducted using a Keyence VHX 7000 digital microscope. The results indicated that increased power output generally led to wider kerf widths, while higher cutting speeds resulted in narrower kerfs. Beech exhibited the narrowest kerfs, followed by oak, with spruce wood showing the widest for TOP surface equal to 415.60 ± 103.05 , 462.24 ± 114.04 , and 497.63 ± 149.05 μm , respectively. Statistical analysis using ANOVA highlighted the significant effects of power output, cutting speed, and wood structures on kerf width. This research offers insights into optimizing laser cutting parameters to achieve precise and efficient cuts in wood processing applications within interval of energy densities between 11.2 and 90 J·mm⁻².

DOI: 10.15376/biores.21.3.6463-6481

Keywords: Laser processing; Kerf variation; Kerf width; CO₂ laser; Wood

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INTRODUCTION

Late in the 1970s, laser cutting progressed from laboratory applications to practical use in commercial manufacturing (Hecht 1992; Shinde and Kubade 2016). This technology offers several advantages over traditional cutting methods, such as precise and clean cuts, elimination of the need for mechanical workpiece holding, and the ability to cut extremely fine contours and various material thicknesses (Lazov *et al.* 2017). Presently, laser cutting is used in specific sectors such as die board cutting, inlay cutting, furniture production, marking, and rapid prototyping (Kolarevic 2001; Grigoriev *et al.* 2022).

To reduce production costs and optimize laser cutting for wood and wood composites, it is essential to consider both the maximum feed rate and cut quality. The input parameters, including laser power and cutting speed, significantly influence the resulting quality (Bernát *et al.* 2018; Mushtaq *et al.* 2020; Sobolewska and Ciecńska 2021). Comprehensive studies are required to assess the cut quality of typical wood species and wood composites (Barcikowski *et al.* 2004). Optimizing laser cutting involves achieving the best geometrical precision while preserving kerf quality (Moradi *et al.* 2020).

Laser cutting, an advanced machining process, utilizes high-intensity beams of light to precisely cut through materials with exceptional accuracy and efficiency (Steen *et al.* 2010; Vagheesan 2014). This process involves converting laser energy into thermal energy, leading to localized melting, vaporization, and material removal from the workpiece (Schuocker 1989; Shinde and Kubade 2016). Thermoset plastics and wood undergo photochemical degradation. This process is accompanied by the production of smoke and the formation of a thin carbon layer at the cut point. (Powell and Kaplan 2004). Laser cutting is known for its speed, minimal kerf width, limited heat-affected zone, reducing the need for post-processing (Decker *et al.* 1984).

In current research into CO₂ laser cutting of wood, several gaps and potential areas for future exploration have been identified. In the previous studies, experiments were carried out according to specific laser parameters to analyze the effects of each parameter on processing quality. Mushtaq *et al.* (2020) highlight the need for further studies to optimize cutting parameters and improve cut quality. Decker *et al.* (1984) emphasize the importance of understanding the material properties and physical mechanisms of the cutting process. Martínez-Conde *et al.* (2017) provide a technical overview of the potential and parameters required for the successful application of CO₂ laser cutting to wood. Radovanovic *et al.* (2011) review experimental investigations on CO₂ laser cutting, focusing on process parameters and cut quality characteristics. Sivaraos *et al.* (2022) report that laser power and cutting speed significantly influence kerf width in Meranti wood, with lower power and higher speed resulting in narrower kerfs.

Guo *et al.* (2021) and Sharma *et al.* (2010) both explore the influence of processing parameters on kerf width in laser cutting. Guo's study on pine wood found that a lower moisture level and slower cutting speed led to a deeper kerf, whereas a higher cutting speed with wet wood produced a narrower kerf, enhancing yield. Sharma's work on nickel-based superalloy showed that kerf quality, including width and taper, was primarily impacted by oxygen pressure, pulse width, and cutting speed for both straight and curved cuts (Sharma *et al.* 2010; Guo *et al.* 2021). Yilbas *et al.* (2017) and Duan *et al.* (2001) provide additional insights into the laser cutting process, with Yilbas discussing the influence of laser output power and cutting speed on kerf width, and Duan presenting a model for predicting the geometric shape of the cut kerf. These studies collectively highlight the importance of processing parameters in determining kerf width in laser cutting, with potential applications in wood and other materials (Duan *et al.* 2001; Yilbas *et al.* 2017). Yilbas *et al.* (2001) found that slight variations in laser power, cutting speed, and energy coupling factor modify the kerf width size considerably, and Xu *et al.* (2017) identified a hierarchy of factors affecting kerf width in laser cutting, ranking them as laser output power, nozzle height, and cutting speed. The study showed that increased laser power significantly enlarged kerf width, while cutting speed had a minimal effect. Additionally, excessive increase in focal length resulted in both widening and shallowing of the kerf (Yilbas 2001; Xu *et al.* 2017). These studies collectively suggest that future research in CO₂ laser cutting of wood should focus on optimizing cutting parameters, understanding material properties, and improving cut quality.

Eltawahni *et al.* (2011) explored the optimization of process parameters for laser cutting medium-density fiberboard (MDF) using a CO₂ laser. By employing a Design of Experiments (DOE) approach, the research examined the effects of laser power, cutting speed, gas pressure, and focal point position on the cutting quality, assessed through measures such as top and bottom kerf widths, the ratio between them, cut section roughness, and operating cost. Findings indicated that focal point position significantly

affected both kerf width and roughness, highlighting the importance of careful parameter selection to balance quality and cost in laser-cutting processes (Eltawahni *et al.* 2011).

Individual species have been previously examined, such as beech by Corleto *et al.* (2024) and Rezaei *et al.* (2022), oak by Maciak *et al.* (2024) and Klement *et al.* (2023), and spruce by Kúdela *et al.* (2023) and Ružiak *et al.* (2024). To the best of available knowledge, no prior publication has investigated kerf width variations across a conifer vs. ring-porous vs. diffuse-porous wood under the same experimental setup and analyzed the relative influence of anatomy vs. density on those outcomes (Rezaei *et al.* 2022; Klement *et al.* 2023; Kúdela *et al.* 2023; Corleto *et al.* 2024; Maciak *et al.* 2024; Ružiak *et al.* 2024).

This study notably examined the impact of CO₂ laser cutting parameters on three distinct wood anatomical structures: ring-porous (oak), diffuse-porous (beech), and coniferous (spruce). While previous studies have investigated laser cutting of wood, few have explored how these distinct anatomical categories, each with unique structural compositions, respond to laser cutting and variations in delivered energy dose E_d . E_d provides in-sight into how energy input interacts with wood structure, potentially leading to refined cutting techniques for different wood types.

This research aimed to map the impact of individual parameters, both material and technological, on kerf width variations resulting from CO₂ laser cutting. The parameters observed included power output, cutting speed, wood species, kerf sides, and delivered energy dose (E_d), which is defined by Eq. 1,

$$E_d = \frac{P}{d \cdot v} \quad (\text{J} \cdot \text{mm}^{-2}) \quad (1)$$

where E_d represents the energy dose in joules per square meter ($\text{J} \cdot \text{mm}^{-2}$), P is the laser power in watts (W), v is cutting speed in millimeters per second ($\text{mm} \cdot \text{s}^{-1}$), and the spot diameter d (mm).

The goal was to quantify the variations in kerf width at both the top and bottom of transverse cuts in spruce, oak, and beech wood. Measurements were conducted using optical measurements with a digital microscope. This analysis aimed to enhance precision in material processing applications by identifying optimal parameter combinations to achieve the desired kerf geometry within interval of energy doses between 11.2 and 90 $\text{J} \cdot \text{mm}^{-2}$.

EXPERIMENTAL

Materials

Beech (*Fagus sylvatica* L.), oak (*Quercus petraea*), and spruce wood (*Picea abies* L.) were selected as the test materials. These species were picked to exemplify a variety, encompassing both deciduous and coniferous trees, as well as ring-porous and diffuse-porous types. The selected species represent a range of anatomical characteristics. Beech is characterized by a relatively uniform cellular structure, oak features prominent large vessels in the latewood, and spruce displays marked density variation between earlywood and latewood.

The sample sizes were 500 mm × 70 mm × 5 mm (*length* × *width* × *thickness*). Prior to laser machining, boards were milled on a jointer, thicknesser, and wide-belt sander to achieve the final thickness and surface quality. The samples were acclimated in an environment of 20 °C and 60% relative humidity. Kerfs, oriented perpendicularly to the wood fibers and measuring 50 mm in length, were cut using a CO₂ laser CM-1309

(Shenzhen Reliable Laser Tech, Shenzhen, China) with a peak power capacity of 135W.

Laser power settings, cutting speeds, and all other parameters can be found in Table 1. The cutting schematic is shown in Fig. 1. The focal point was set at the material surface.

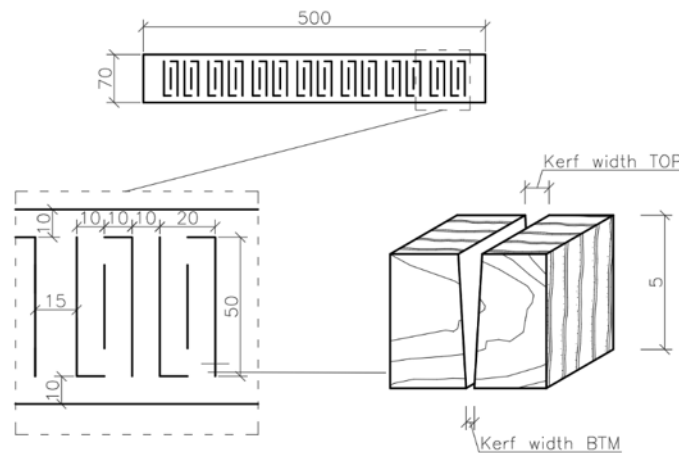


Fig. 1. Schematic of the sample for kerf width measurement

Table 1. Parameters Used in the Laser Experiment

Parameter	Value
Power output (P) (W)	67.5 (50%), 101.2 (75%), 135 (100%)
Cutting speed (v) ($\text{mm}\cdot\text{s}^{-1}$)	5, 10, 20
Wood species	Oak, Beech, Spruce
Wavelength (μm)	10.6
Focal length (mm)	50.8
Beam spot diameter (d) (mm)	0.3
Nozzle standoff distance (mm)	10
Assistant gas	Compressed air
Assistant gas pressure (bar)	0.35
Cutting direction	Perpendicular

Methods

Kerfs were digitized into 3D models (Fig. 3) using the imaging capabilities of the Keyence VHX 7000 (Keyence Corporation, Osaka, Japan) digital microscope (Fig. 2).

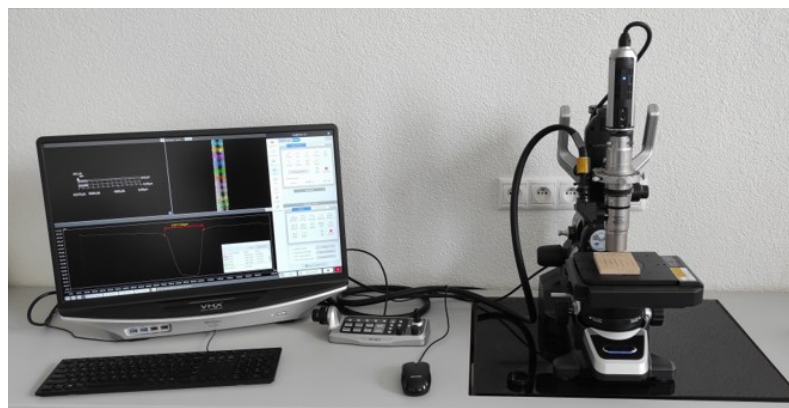


Fig. 2. Keyence VHX 7000 digital microscope

This process involved scanning areas measuring 30×2.5 mm to achieve high-resolution 3D representations. Following the digitization, the profile measurement function of the Keyence VHX 7000 (Keyence Corporation, Osaka, Japan) was utilized, under a magnification level of $\times 100$, to conduct precise measurements of the kerfs' widths.

The kerf width is defined as the horizontal distance between the intersection points of tangents drawn along the upper sections of the kerf walls and the tangent to the material surface on either side of the cut. The measurement was performed using the VHX-H5M module, which is part of the VHX-7000 digital microscope system, as shown in Fig. 3.

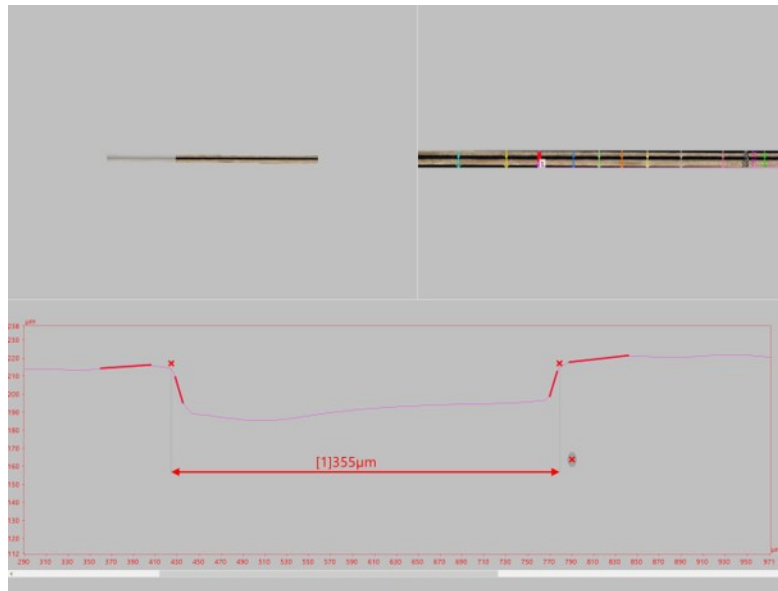


Fig. 3. Example of kerf measuring in Keyence interface

An alternative approach to evaluating parameter impact was identified during the initial analysis of the data obtained. The primary laser parameters used in the experiments were laser power (P) and cutting speed (v). However, it was found that a supplementary parameter, delivered energy dose (E_d) provides additional insight. This parameter represents the amount of laser energy delivered to the material per unit area along the cutting path. To quantify this, the delivered energy dose was calculated using Eq. 1. Doses for the combination of parameters are shown in Table 2.

Table 2. Energy Doses Corresponding to Combinations of Parameters

Power (P) (W)		67.5	101.25	135
	Speed (v) (mm·s ⁻¹)	Energy Dose (E_d) (J·mm ⁻²)		
	5	45	67.5	90
	10	22.5	33.75	45
	20	11.25	16.875	22.5

RESULTS AND DISCUSSION

The data set was subjected to statistical evaluation using the STATISTICA 12 software (StatSoft, Tulsa, USA). The dataset was preprocessed to address potential outliers using standardized criteria. Normality was assessed using the Shapiro-Wilk test, with each group exhibiting homogeneity of variances, confirmed through Levene's test. The data were sorted into relevant categories, and descriptive statistics (Table 3) were computed to validate the assumptions of factorial ANOVA: (1) normality, where the dependent variable is normally distributed; (2) independence of observations and groups; and (3) equality of variances across factors. A multi-factor analysis of variance, including interactions, was subsequently conducted. These preparation steps ensured the robustness of the results, facilitating reliable and accurate comparisons across samples. The p-values resulting from the analysis are presented in Table 4.

Table 3. Results of Descriptive Statistics for Kerf Widths

Species	Side	N	Mean (µm)	Median (µm)	STD	Min (µm)	Max (µm)	Variance (µm ²)	CV (%)
Beech	BTM	180	375.30	350.65	154.28	146.80	724.70	23801.15	41.11
Beech	TOP	180	415.60	403.70	103.05	182.30	656.20	10620.04	24.80
Oak	BTM	180	440.26	416.95	176.98	128.00	836.80	31323.20	40.20
Oak	TOP	180	462.24	448.65	114.04	252.90	824.50	13004.40	24.67
Spruce	BTM	180	547.91	534.00	142.97	291.80	911.80	20439.61	26.09
Spruce	TOP	180	497.63	448.75	149.05	287.90	936.80	22216.29	29.95

Table 4. p-values from Multi-Factor Analysis of Variance (ANOVA)

Effect	p-value
Tree species	0.000*
Side	0.291
Power output	0.000*
Cutting speed	0.000*
Tree species*Position	0.000*
Tree species*Power output	0.002*
Tree species*Cutting speed	0.006*
Power output*Cutting speed	0.000*
Tree species*Power output*Cutting speed	0.006*
Tree species*Position*Power output*Cutting speed	0.000*

* Statistically significant effect

Influence of Wood Species

Kerf width produced by CO₂ laser cutting was examined across three wood species, as shown in Fig. 4. The experimental results demonstrate that kerf width varied significantly depending on the species. Beech exhibited the narrowest kerf, followed by oak, while spruce samples produced the widest kerf. This finding suggests that kerf width is not determined solely by physical properties such as bulk density; rather, anatomical structure appears to play a substantial role in kerf formation and the wood's behavior during laser processing.

Jang *et al.* (2022) reported a significant positive correlation between bulk density and thermal conductivity in different species of wood, suggesting that higher bulk density

leads to increased thermal conductivity. This relationship may also influence the response to kerf creation and its characteristics based on wood density (Jang and Kang 2022). Certain impacts of density and growth rings, as well as their interactions with a laser beam, were examined in previous research by Adamčík *et al.* (2023). They stated that the thermal properties of wood significantly influence both the cut width and the quality of the cut surface. Lower thermal conductivity results in heat accumulation at the cutting position, as heat is not effectively dissipated into the surrounding material. This accumulation leads to localized spreading of the cutting kerf due to the increased rate of thermal degradation of the wood (Adamčík *et al.* 2023).

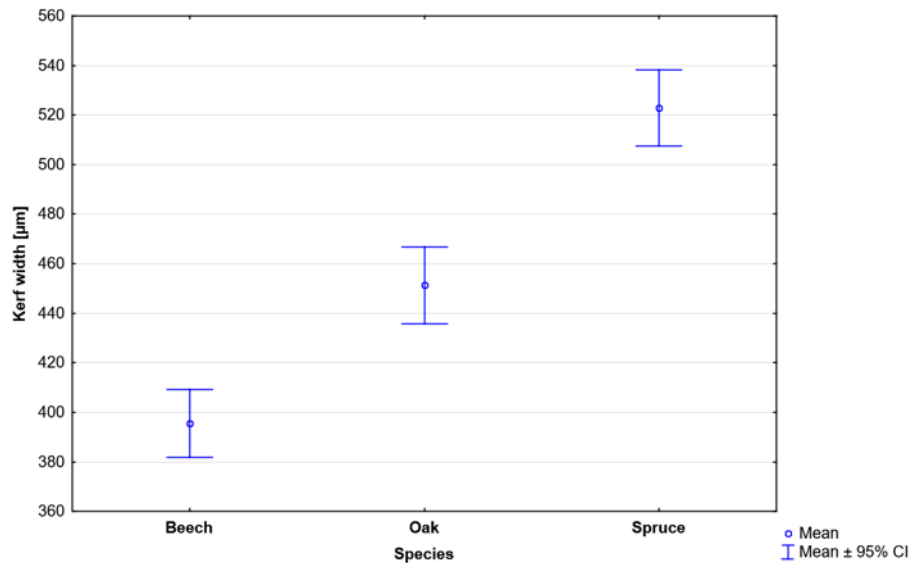


Fig. 4. Kerf widths across different species

Comparison of Kerf on Both Sides of Cut

Figure 5 presents a comparison of the kerf width on the bottom (BTM) and the top (TOP) sides of the material. The kerf was wider on the top side of the workpiece. Prior CO₂ cutting work showed that material can require higher effective energy for penetration and may promote heat accumulation near the entry region, contributing to wider kerf openings, especially under low-speed/high-power conditions (Der 2025). However, there was a significant overlap in width for both sides, which is supported by the results of ANOVA in Table 4, as this was the only statistically non-significant effect in the present analysis.

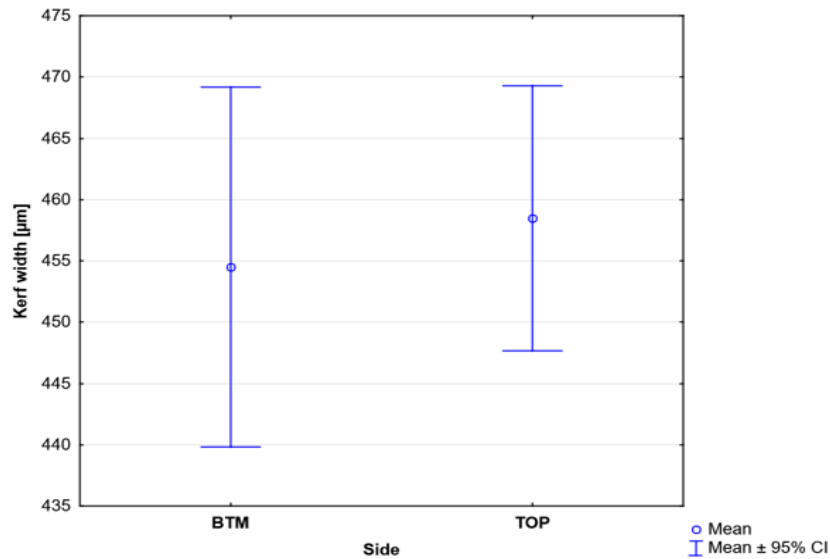


Fig. 5. Kerf widths variations on top and bottom side of the cut

While Fig. 5. provides an overall comparison of kerf widths, Fig. 6 offers a more detailed view by species and sides of the cut, revealing important differences in kerf shape and behavior. For beech and oak, both hardwoods, the kerf followed the expected V-shape geometry, where the top-side kerf is narrower than the bottom, indicating a typical taper caused by beam divergence and heat accumulation.

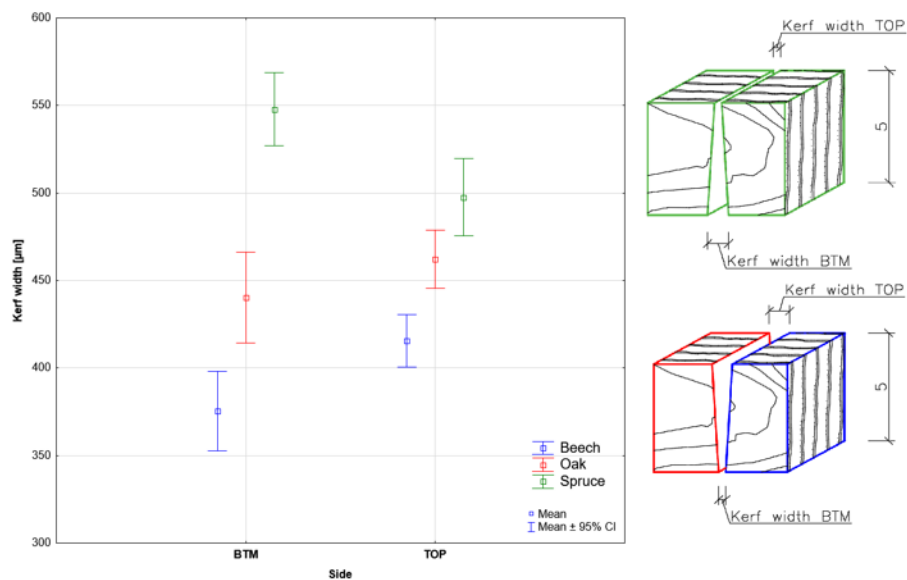


Fig. 6. Kerf width variations on top and bottom of the cut across species

In contrast, spruce showed a reversed trend, with wider kerfs at the bottom than at the top, deviating from the standard V-profile. This inversion of taper direction may be associated with spruce anatomical heterogeneity (earlywood–latewood contrast), which can lead to non-uniform heating and material removal along the cut front. Since microscopy/thermal imaging was not performed, this explanation is proposed as a hypothesis based on repeatability across spruce replicates and literature reports of irregular

kerf formation in softwoods. This observation is consistent with findings by Guo *et al.* (2021), who reported that such structural heterogeneity in softwoods often leads to irregular kerf profiles and poor edge quality.

The inverted taper in spruce suggests a non-optimal choice of processing parameters, particularly the combination of high power and low speed, which causes excessive thermal loading at the surface and insufficient energy penetration deeper into the cut. As previously noted, coniferous species such as Spruce tend to yield better cutting quality when processed at higher cutting speeds and lower power outputs, as this reduces surface charring and improves energy distribution (Barcikowski *et al.* 2004).

Interactions Between All Parameters

Kerf width analysis top vs. bottom side

Kerf width trends observed across the tested power and speed settings reveal distinct differences between species and cutting sides, as well as notable interactions between parameters.

On the bottom side of the cut (Fig. 7), kerf width decreased with increasing cutting speed and increased with higher laser power, a trend that was true for all tested species. However, the magnitude of change differed substantially by material. Spruce exhibited kerf widths up to 70 to 100% wider than beech, particularly at low cutting speeds ($5 \text{ mm} \cdot \text{s}^{-1}$) and high-power settings (75 to 100%). For instance, at 75% power and $5 \text{ mm} \cdot \text{s}^{-1}$, spruce kerf width exceeded $700 \mu\text{m}$, while beech remained below $400 \mu\text{m}$. Oak fell consistently between the two, with kerf widths approximately 20 to 40% greater than beech under the same conditions.

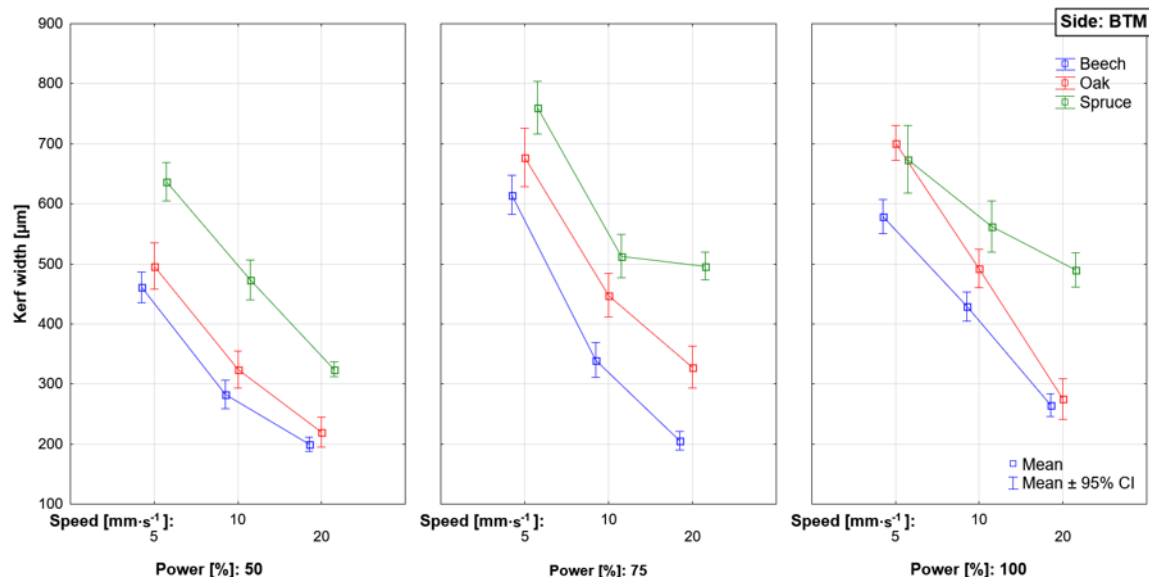


Fig. 7. Combination of all parameters on the bottom side of the kerf

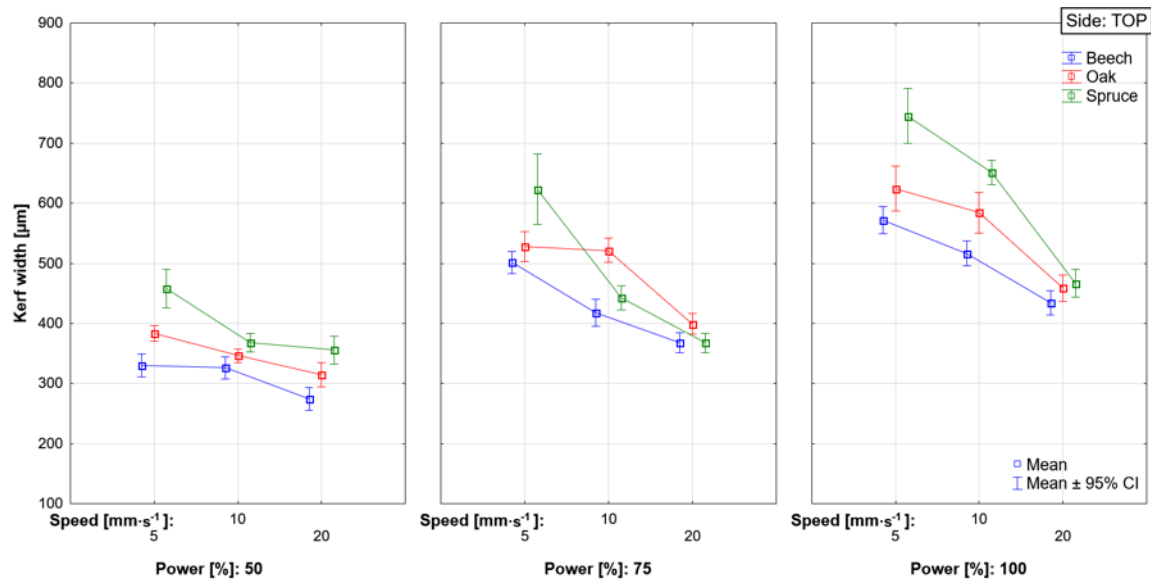


Fig. 8. Combination of all parameters on the top side of the kerf

Such a pattern aligns well with findings by Yang *et al.* (2022), who observed that lower density and heterogeneous anatomy in softwoods like spruce result in broader and more inconsistent kerfs due to greater sensitivity to thermal energy. The greater error bars observed in spruce at low speeds and high-power further support this, reflecting increased variability in cutting performance and material response. In contrast, beech wood exhibited the most stable and narrow kerfs, which is consistent with the observations of Rezaei *et al.* (2022), who identified beech as a reliable species for laser processing due to its uniform pore structure and moderate density.

Oak, with its distinct vessels and ring-porous structure, demonstrated intermediate behavior, more variable than beech but generally more predictable than spruce. This consistency in response across species, despite anatomical differences, supports the conclusions of Riveiro *et al.* (2012), who noted that processing parameters such as power and speed dominate kerf geometry, though the scale of their effect is material-dependent.

On the top side of the cut (Fig. 8), the same overall trend was observed for kerf width, which decreased with speed and increased with power, but the absolute values were 15 to 25% narrower compared to the bottom side. This reflects the typical taper effect of laser cutting, where beam divergence and material char buildup contribute to kerf expansion on the exit side. For example, beech at 100% power and 20 mm·s⁻¹ showed a top-side kerf width of 320 μm, compared to 380 μm on the bottom a reduction of roughly 16%. In spruce, the taper was less pronounced (10 to 12%), potentially due to uneven energy absorption and incomplete material ejection.

Interestingly, while absolute kerf widths differed across species, the directional behavior (wider kerfs with more power, narrower kerfs with more speed) remained consistent, especially between the two hardwoods. This partially contrasts with the conclusions of Açıık and Tutuş (2022), who suggested that each species requires uniquely optimized parameters. Although Basar (2025) investigated ABS rather than wood, their finding that cutting speed strongly governs kerf width through its control of laser material interaction time provides a useful parallel for interpreting the present results. Likewise, in this study cutting speed exerted the strongest influence on kerf geometry, while power effects were mainly conditional and most evident at low speeds. At the same time, wood

introduces additional structure-driven variability. Therefore, the magnitude and in some cases even the direction of taper can differ between species under identical parameter sets. Overall, these findings suggest that species-specific calibration may be required for fine-tuning, but the underlying response patterns to speed and power can be transferable within anatomically similar wood groups (e.g., diffuse-porous hardwoods).

In terms of quantitative trends:

- Doubling cutting speed from 10 to 20 mm·s⁻¹ reduced kerf width by 30 to 40% in beech and oak.
- Increasing power from 50% to 100% can widen the kerf by up to 70% in spruce and 40 to 60% in oak and beech.
- The interaction effect between speed and power was strongest in spruce, where combinations of high power and low speed produce the widest and least consistent cuts.

Among all species, beech consistently offered the narrowest, most stable kerf widths, making it the most suitable candidate for applications requiring high dimensional accuracy. Due to its anatomical variability and sensitivity to processing conditions, spruce may require tighter process control or adjusted focus settings to maintain cut quality. This is supported by Wust *et al.* (2002), who emphasized the role of density fluctuations and resin content in influencing cut consistency in softwoods (Wust *et al.* 2002).

Taken together, these results support broader literature consensus: kerf width is highly sensitive to laser power and cutting speed, and while material properties modulate the effect, the direction of response remains predictable.

Using interpolation from measured data, kerf width can be predicted based on power output and cutting speed across all three species, as illustrated in Fig 9. These 3D graphs create a mesh that visualizes a broad range of parameter interactions. While not the most precise, these graphs effectively capture the trends of kerf width behavior, providing a visual tool for understanding and anticipating kerf variations across different settings. By leveraging this interpolation, we gain foresight into how kerf widths respond to changes in power and speed, enhancing our ability to optimize laser-cutting processes for beech, oak, and spruce wood.

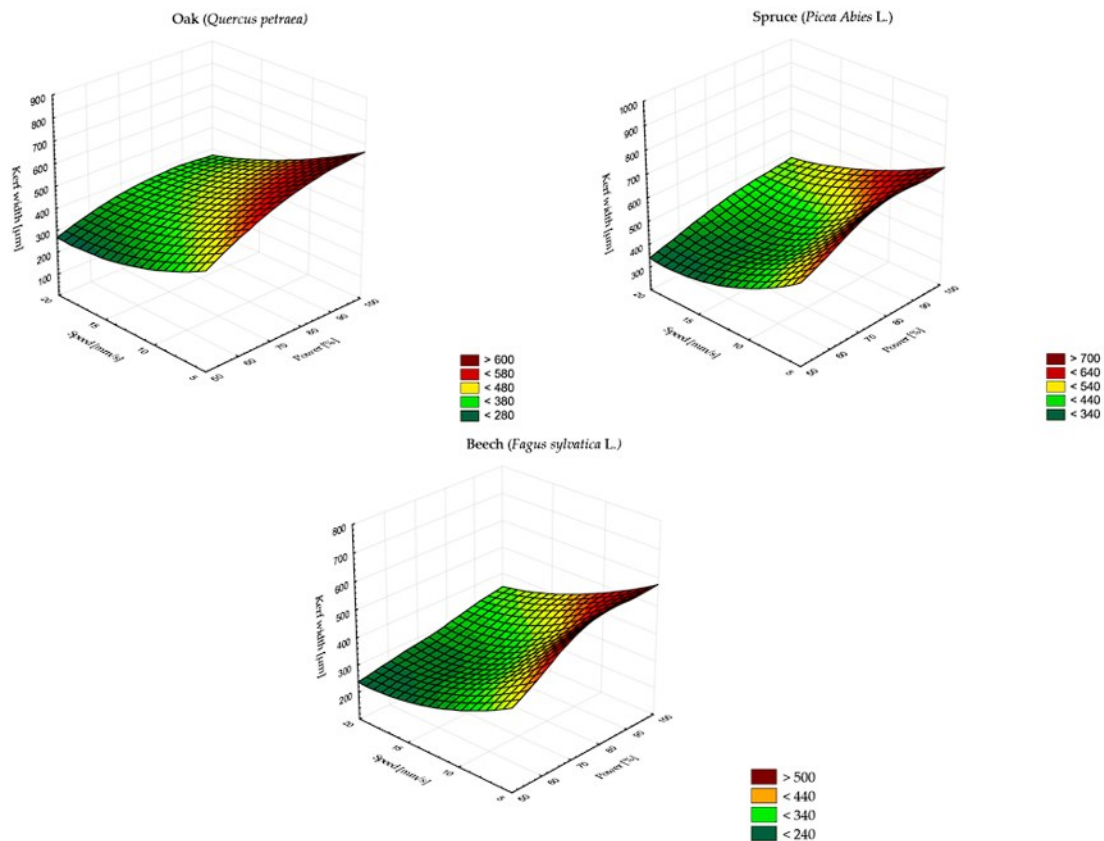


Fig. 9. 3D interpolation of kerf width variations based on power output and cutting speed for all species

Impact of joint factor E_d on kerf width

Parameters E_d , side, and species were once again subjected to the multi-factor analysis of variance with interaction (ANOVA), and the resulting p-values resulting from this ANOVA are presented in Table 5.

Figure 10 illustrates the relationship between delivered energy dose (E_d) and kerf width for beech, oak, and spruce. By combining power and speed into a single metric, E_d offers a more coherent view of how laser energy interacts with different wood anatomies. Effect of E_d on kerf width value in studied interval, demonstrates linear trend, which characteristics are listed in Table 6.

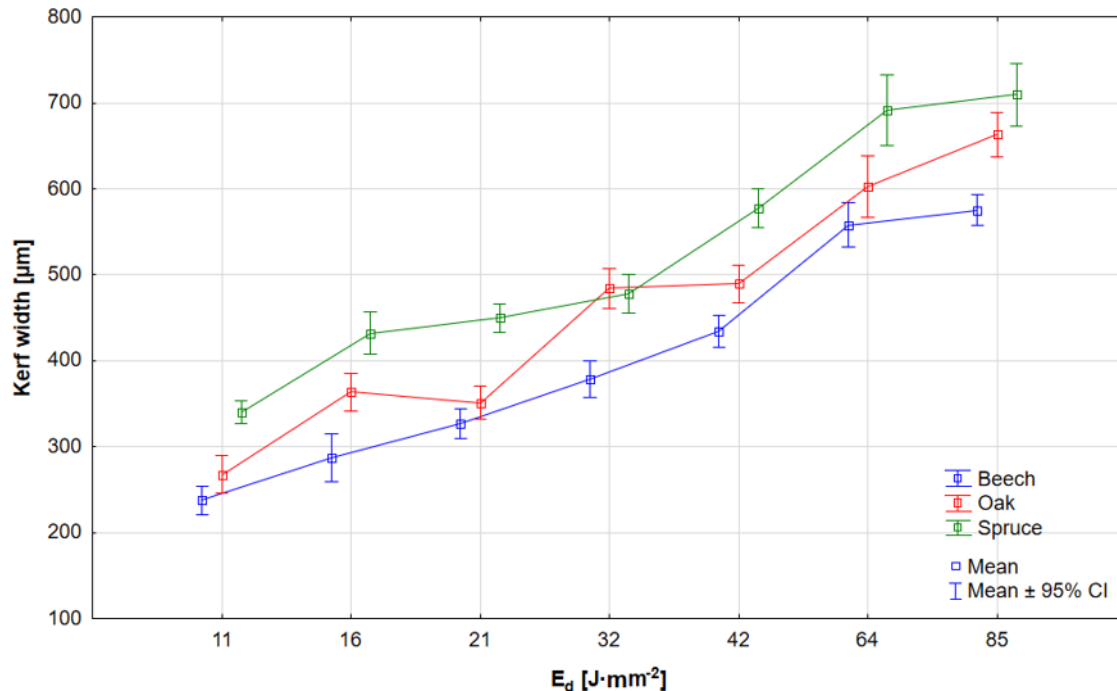


Fig. 10. Impact of varying energy doses on kerf width across tested wood species

Table 5. p-Levels from the Second Multi-Factor Analysis of Variance (ANOVA)

Effect	p-value
E_d	0.000*
Tree Species* E_d	0.000*
Side* E_d	0.000*
Tree Species*Side* E_d	0.000*

* Statistically significant effect

Table 6. Effect of E_d on Kerf Width Value for Different Species

Material	R ²	MAPE (%)	Slope (10 ⁻³ mm ³ ·J ⁻¹)	Absolute value (μm)
Spruce	0.937	5.66	2.28	330
Beech	0.954	5.85	2.30	214
Oak	0.936	7.30	2.43	256

Across all species, an increase in energy dose correlated with a progressive widening of the kerf, confirming that higher energy input intensifies thermal degradation and material removal. These findings are consistent with those of Uslan (2005), who demonstrated a direct relationship between energy density and cut width in wood processing.

Among the tested species, beech exhibited the most linear and stable response, with kerf width increasing gradually as E_d rose from 230 μm at 23 J·mm⁻² to 570 μm at 180 J·mm⁻², as shown in Table 6. The relatively low variance across the energy range reflects the uniform structure of diffuse-porous hardwoods, where cell distribution and density are consistent, resulting in predictable thermal response.

Oak, a ring-porous hardwood, showed a more stepwise increase in kerf width. At lower E_d levels, kerf width remained relatively stable (300 to 400 μm), but it began to rise

more sharply after $68 \text{ J}\cdot\text{mm}^{-2}$, reaching over $650 \mu\text{m}$ at the highest energy input. The moderate variability observed reflects the influence of anatomical features, such as large vessels in the latewood, which alter how laser energy is absorbed and dissipated, especially as dose increases.

In contrast, spruce displayed the steepest and most variable increase in kerf width, ranging from $280 \mu\text{m}$ at $23 \text{ J}\cdot\text{mm}^{-2}$ to over $700 \mu\text{m}$ at $180 \text{ J}\cdot\text{mm}^{-2}$. This pronounced response can be attributed to the high contrast between earlywood and latewood densities, with earlywood around $373 \text{ kg}\cdot\text{m}^{-3}$ and latewood at $713 \text{ kg}\cdot\text{m}^{-3}$ (Franceschini *et al.* 2012). This causes non-uniform energy absorption, localized burning, and uneven kerf formation. The variability in kerf width is especially evident at higher E_d values, indicating reduced cutting stability and greater susceptibility to overburn and edge charring.

While all species showed a positive correlation between E_d and kerf width, the rate of increase and variability were strongly influenced by wood anatomy (Yusoff *et al.* 2008).

In general, for low values of E_d it is possible to conclude that effect of this parameter on kerf width according to R^2 value and MAPE value can be considered as linear. MAPE values between 5 and 8% belong to lower ones for wooden materials where even 10% MAPE value is considered as very good. The coefficient of determination R^2 between 0.936 and 0.954 is also good value because this trend does not consider side of sample and take laser power P and cutting speed v effect only through E_d value and no single effect of them, which are most affecting kerf width, as shown in results and by many other authors. The slope did not exhibit affecting by wood species, as differences between materials were minimally 0.9% and maximally 6.6%, which lie in interval of MAPE error value. Spruce exhibited the largest absolute kerf width, significantly higher than beech and oak. Similar tendencies have been reported in the literature, where materials with lower bulk density frequently produce wider kerfs under comparable cutting conditions.

Figure 10 shows that at higher values of E_d , kerf width stabilized, which is in good agreement with results of many other authors as kerf width exhibits such trend *versus* laser power P value.

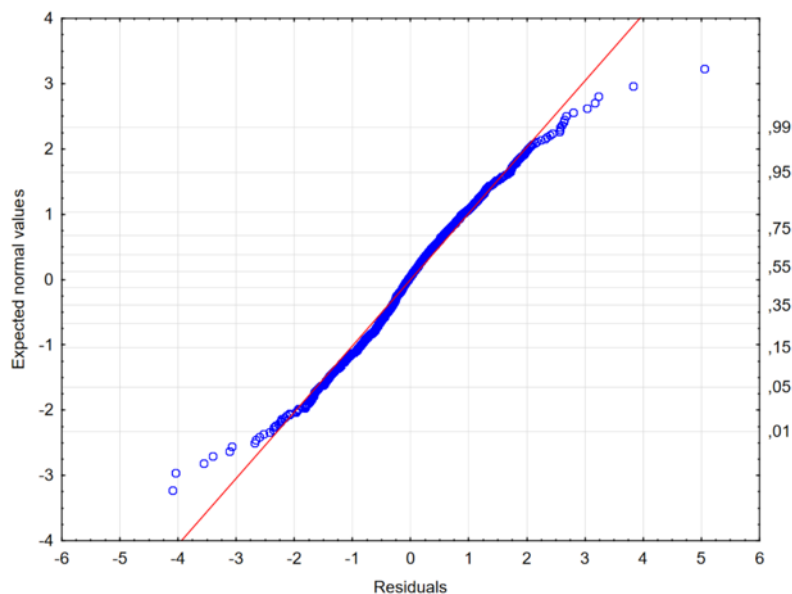


Fig. 11. Normal Q-Q plot of standard residuals

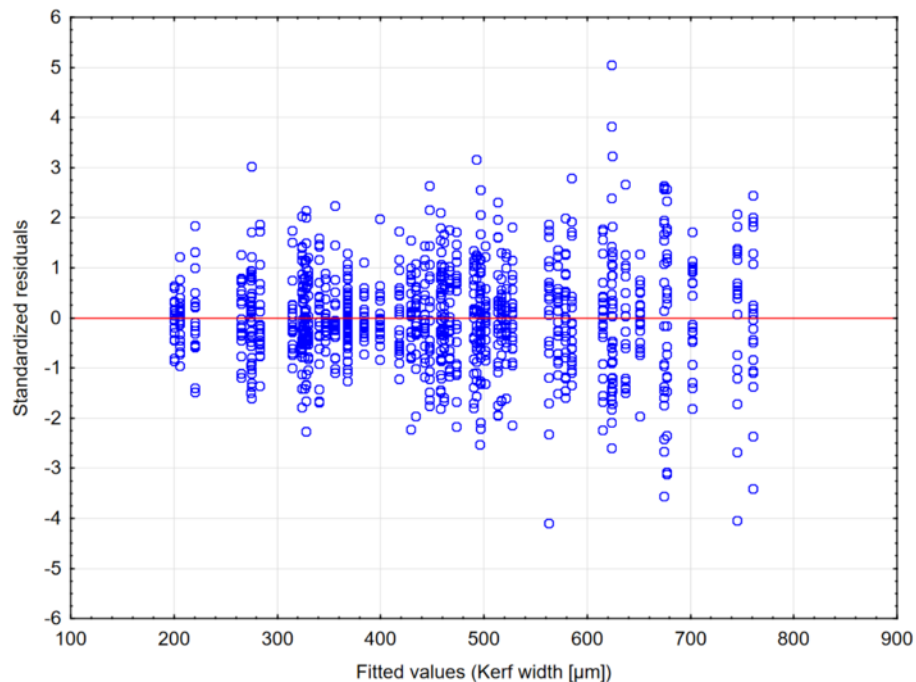


Fig. 12. Residuals versus fitted values (homoscedasticity check)

ANOVA assumptions were evaluated using residual diagnostics. Normality was assessed using the Shapiro–Wilk test and normal probability (Q-Q) plots of standardized residuals (Fig. 11). Homoscedasticity was examined using plots of standardized residuals versus fitted values (predicted values) and Levene’s test (Fig. 12).

The Q-Q plot (Fig. 11) was approximately linear over the central range with minor tail deviations, and the residuals-versus-fitted plot showed no pronounced funnel-shaped pattern; the vertical banding reflects discrete fitted values typical of factorial ANOVA.

CONCLUSIONS

1. Delivered energy dose (E_d) was found to be a useful descriptor of kerf behavior compared to analyzing cutting speed and power independently. Across all species, kerf width increased with E_d linearly with R^2 value between 93.5% to 95.5% and MAPE values between 5.66 and 7.30%, as shown in Table 6.
2. The slope of kerf widths versus E_d value did not show significant effect of material type with fluctuations between 0.9% and 6.6%, which were lower than MAPE values.
3. Table 6 shows effect of wood species on kerf width. Low bulk density spruce wood (compared to beech and oak) exhibited significantly higher values of kerf width. This variability was strongly species-dependent, demonstrating the influence of wood anatomy on thermal response.
4. Beech consistently produced the narrowest and most stable kerf widths, with low variability across all cutting conditions. Its uniform anatomical structure enables predictable interaction with the laser beam.

5. Oak showed intermediate behavior, with kerf width strongly influenced by its ring-porous structure, especially the presence of large vessels in latewood.
6. Spruce exhibited the widest and most inconsistent kerfs, especially at high power and low cutting speed. Its sharp earlywood–latewood density contrast led to uneven energy absorption, irregular kerf shapes, and, in some cases, inverted taper (narrower kerf at the bottom than the top). This behavior suggests higher cutting speeds and lower power to minimize surface charring and overburn.
7. While cutting speed and laser power significantly affected kerf width, the trends remained consistent across species: higher speeds reduced kerf width, while higher power increased it. However, absolute values and stability varied significantly, depending on species anatomy.
8. The apparent differences in kerf width between the top and bottom sides suggest further investigation into the laser beam profile.

ACKNOWLEDGMENTS

This work was supported by the Slovak Research and Development Agency under the Contract no. APVV-20-0159 and by the VEGA Agency of the Ministry of Education, Research, Development and Youth of the Slovak Republic and the Slovak Academy of Sciences Grant no. 1/0577/22 and Grant no. 1/0179/25.

Conflict of Interest

The authors declare no conflicts of interest.

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Article submitted: October 15, 2025; Peer review completed: December 1, 2025; Revised version received: March 3, 2026; Accepted: March 6, 2026; Published: May 27, 2026.
DOI: 10.15376/biores.21.3.6463-6481