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Preserving Tradition with Technology: CO₂ Laser Engraving of Lampung *Tapis* on Wood Waste

Wahyu Hidayat*, Bagus Saputra, Alim Fadila Rahman, Intan Fajar Suri, Indra Gumay Febryano, Duryat Duryat, and Dian Iswandaru

Abstract

The traditional motif known as *Tapis* holds profound artistic and cultural value for the Lampung ethnic group. Promoting and preserving this motif is imperative to ensure its continued recognition within and beyond the Lampung region. A promising solution addresses this issue by applying innovative, creative, and solution-oriented technologies like CO_2 laser engraving on wood waste. The CO_2 laser engraving system changes electrical power into infrared radiation, enabling it to produce precise designs on various materials. The material's artistic and economic value increases when a CO_2 laser engraves the *Tapis* motif onto wood waste. Using wood as a carbon-rich medium supports carbon storage and can help avoid greenhouse gas emissions that are otherwise associated with open burning or uncontrolled decomposition of wood waste. This study evaluated the impact of different laser power levels (2.5, 5.0, and 7.5 W) on the appearance of Meranti wood surfaces after engraving. The evaluation of brightness (L^*), red/green chromaticity (a^*), and yellow/blue chromaticity (b^*), along with overall color change (ΔE^*), was conducted using the CIE-Lab system, in conjunction with consumer preference assessments. Quantitatively, L^*, a^*, and b^* decreased from 72.35, 12.33, and 18.49 in the control to 32.03, 1.21, and 5.73 at 7.5 W as maximum laser power, respectively. Consistent with these shifts, ΔE^* increased from 30.04 at 2.5 W to 42.52 at 5 W and 43.73 at 7.5 W, all categorized as "total color change". The consumer evaluation favored darkened color modifications. The results clearly demonstrate that CO_2 laser technology not only enhances the visual appeal of wood waste products through engraving but also adds economic value and promotes environmental sustainability by capturing carbon. This powerful combination highlights the technology's potential as a sustainable and profitable solution for wood waste utilization.

Keywords: carbon sequestration, CO_2 laser, *Tapis*, wood waste, cultural preservation

1. INTRODUCTION

Indonesia is one of the largest archipelagic countries in the world, with a population of 271 million people [1], and is well known for its abundant arts, culture, and local wisdom [2]. In particular, Lampung has a high value of cultural heritage, reflecting the creativity and craftsmanship of past generations [3]. *Tapis* has been regarded by the Lampung people as a "symbolic medium" for a long time, used to uphold harmony between life, the environment, and the Creator [4]. Tapis is a traditional motif characterized by intricate decorative patterns that express Lampung's distinctive aesthetic identity [3]. Lampung's motto, "*Sai Bumi Ruwa Jurai*" (one earth, two worlds),

refers to its two indigenous groups, the Pepadun and Saibatin [5][6]. Each group maintains its own repertoire of *Tapis* motifs, which are designed for specific ceremonial needs. In practice, *Tapis* is worn or displayed in marriage rites, title-bestowal (*adat*) ceremonies, and other rites of passage, where specific motifs and arrangements signal the wearer's social status and role within the procession [4].

Beyond its aesthetic value, *Tapis* functions as a cultural record and a guide to proper conduct in ritual space. Recurrent symbols—such as ships and the life tree—encode narratives of mobility, kinship, fertility, and stewardship of land and sea, and their placement and repetition help identify stages of a ceremony and the responsibilities of participants [7]. This depth of meaning underlines why preservation is urgent: declining numbers of skilled makers, reduced transmission to younger generations, and shifting ceremonial practice risk severing the link between motifs and their lived contexts. Clear documentation of the ceremonial uses and meanings of *Tapis*, together with culturally appropriate forms of safeguarding (including accurate reproduction on durable media and community-led education), is therefore essential to maintain its function within Lampung society and

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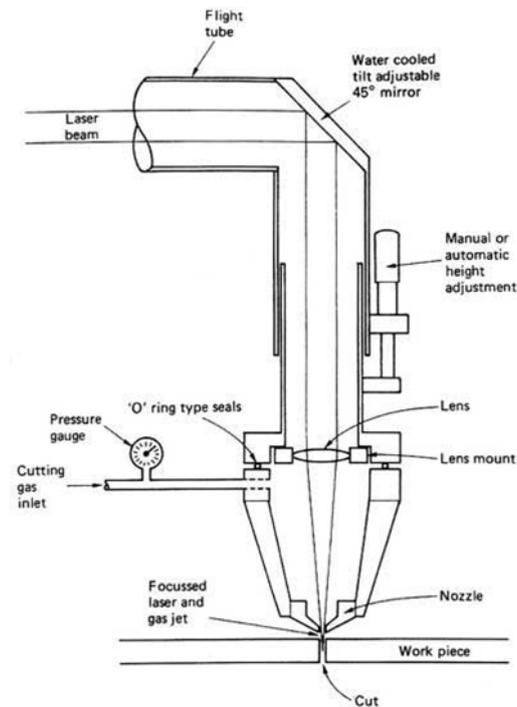**Figure 1**. The working principle of the CO_2 laser.

Table 1. Color change classification [31].

No	Classification value	Description
1	$0.0 < \Delta E^* \leq 0.5$	Negligible
2	$0.5 < \Delta E^* \leq 1.5$	Slightly perceivable
3	$1.5 < \Delta E^* \leq 3.0$	Noticeable
4	$3 < \Delta E^* \leq 6$	Appreciable
5	$6 < \Delta E^* \leq 12$	Very appreciable
6	$\Delta E^* > 12$	Total color changed

to support the communities who steward this heritage [8]. The advancements in technology and the influence of external culture have led to cultural heritage, such as *Tapis*, becoming less popular and even endangered, at risk of disappearing from society [3]. The combined effects of globalization-driven fashion trends and the large-scale production of inexpensive textiles are accelerating the decline of *Tapis*, weakening both the community of artisans and the intergenerational transmission of weaving skills on which its continuity depends [9][10]. Field observations in Lampung reveal that many younger generations now regard *Tapis* primarily as ceremonial attire and seldom acquire the time-consuming embroidery skills that embody its cultural symbolism [11]-[13]. Without timely intervention, as reported in Indonesia's 2016 Cultural Statistics, as many as 167 distinct forms of local wisdom—including *Tapis*—are at risk of disappearing [2].

Traditional preservation methods—such as community-based workshops, hand-crafted replicas, and curated museum collections—encounter three persistent challenges: (i) very low production rates, with traditional looms adding only a few centimeters of fabric per day; (ii) high production costs that limit accessibility; and (iii) progressive pattern distortion during repeated manual reproduction, which diminishes the accuracy of symbolic motifs [11]. These limitations underscore the need for complementary, technology-based approaches that can rapidly reproduce intricate designs while maintaining high fidelity to the original patterns. There is a possibility of preserving regional cultural heritage through technological advancements. Carbon dioxide (CO_2) light

amplification by stimulated emission of radiation (laser) engraving offers a potential solution to these challenges by translating digital motif designs directly into high-contrast engravings on organic substrates such as wood, bamboo, or textile waste. Laser technology, including CO_2, utilizes a mixture of CO_2 and other gases, stimulating them through an electrical process to operate precisely [14][15]. In comparison to manual carving or screen printing, laser engraving provides sub-millimeter precision, consistent replication across large production batches, and minimal tool wear, while operating at power efficiencies of approximately 5–20% of electrical input [16][17]. Research on wood products further indicates that careful adjustment of laser parameters can enhance edge definition and reduce surface roughness, preserving the fine symbolic details that are central to the *Tapis* motif [18]-[20]. Applying this technique to locally sourced wood waste not only supports the preservation of cultural heritage but also produces value-added craft products that strengthen rural economies and contribute to carbon-sequestration objectives.

A potential medium for CO_2 laser engraving is wood waste. Wulandari [21] states that wood waste is a byproduct of production, consisting of wood fragments of variable shape and size with little economic value. Using wood waste as an engraving medium can reduce the cost of raw wood materials. According to data from the Ministry of Environment and Forestry in 2021, Indonesia has a total forested area of 125 million ha, of which 95.6 million ha is forested land, representing 50.9% of the country's total land area [22]. Indonesia produced an estimated 53.12 million m^3 of logs from natural and plantation forests in 2020. It is estimated that the average wood harvesting waste in natural forests is 13–15% of the total yield [23][24], and in plantation forests, up to 20% [25]. Appropriate technology can repurpose wood harvesting waste into high-value products rather than disposing of it. This waste can be reprocessed through advanced technologies, such as CO_2 laser engraving, to increase its economic value, converting it into artistic and functional products [21][26].

This study examines the effect of CO_2 laser engraving in preserving *Tapis* motifs on wood waste media. The use of wood waste as a medium for engraving *Tapis* motifs has many advantages. In addition to the preservation of regional cultural heritage and the economic value of wood waste, this approach also contributes to mitigating global warming through the reduction of greenhouse gas emissions, one of the major causes of global warming [27][28]. The natural process of photosynthesis during tree growth causes chlorophyll in green leaves to absorb carbon dioxide from the atmosphere. This process, aided by water, enables the production of proteins and carbohydrates and stores carbon as a carbon stock in the tree biomass [29]. Utilizing wood waste as a medium for CO_2 laser engraving prevents it from decomposing and oxidizing, thereby releasing stored CO_2 into the atmosphere that would otherwise be released, and thereby reducing greenhouse gas levels. Reducing the release of CO_2 is a way to mitigate global warming, which has a wide range of impacts on different sectors of human life. Global climate change, the melting of the polar ice caps and rising sea levels, and the disruption of many ecological systems are some of these effects [30].

Figure 2. Visual representation of meranti wood after CO_2 laser engraving at different power levels.
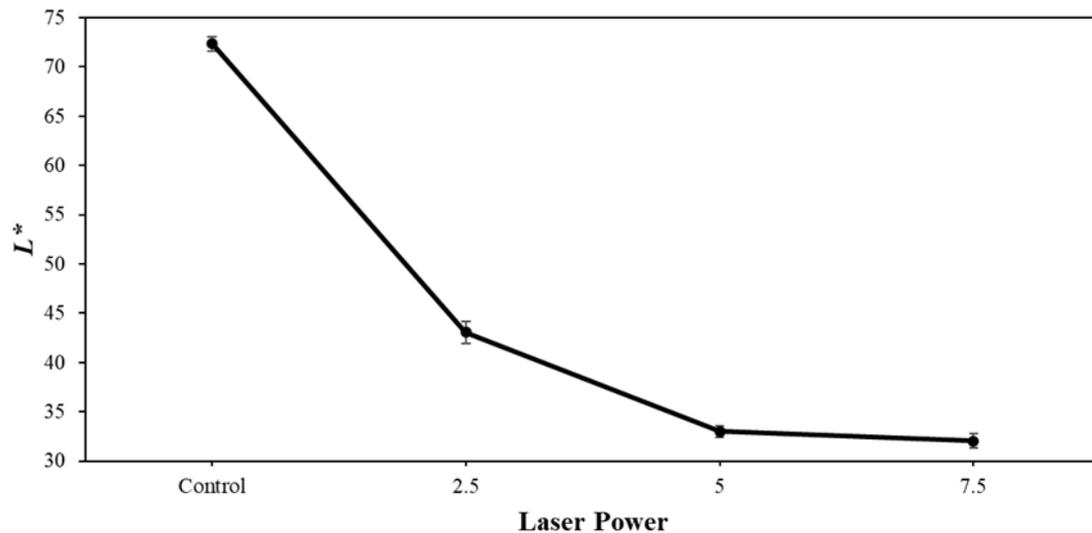
Figure 3. Effect of CO_2 laser power on the brightness change ($L*$) of Meranti wood.

2. MATERIALS AND METHODS

2.1. Materials

Meranti (*Shorea* spp.) wood waste sourced from the furniture industry (offcuts/retired panel pieces) was resized to 30 cm × 20 cm × 5 cm (length × width × thickness). Before machining, the boards were sun-dried or air-dried outdoors to achieve a uniform moisture content (±15%) and minimize warp/twist risk during storage without any chemical pre-treatment. Proper air/sun drying helps control moisture content and minimizes drying-related warping, such as twist. Before engraving, boards were sanded with P320 (extra-fine) grit to obtain a smooth, uniform surface so that laser–material interaction was not confounded by machining marks or raised grain [18]. Laser engraving was conducted at the Forest Products Technology Laboratory, Department of Forestry, Faculty of Agriculture, University of Lampung on a CNC LS-6040 CO_2 laser (nominal max 50 W; 600 × 400 mm work area), at a fixed speed of 50 mm s^{-1} in a single raster pass with the manufacturer-recommended focus. Color analysis was conducted using a colorimeter (AMT507, Amtast, Lakeland, United States) based on the CIE-Lab color space system.

2.2. Methods

2.2.1. Wood Laser Process

The CO_2 laser consists of various parts, as presented in Fig. 1. The pumping device on the engine will charge the CO_2 gas atoms. The excited atoms will emit photons, causing movement due to electromagnetic waves. The resulting laser beam will propagate through the light tube and be reflected by the glass. Then, it will pass through the lens, allowing the laser beam to be focused and engrave and cut the work field with high precision. Three Meranti wood boards were used in this study. For the CO_2 laser engraving process, laser powers of 2.5, 5.0, and 7.5 W were applied. Each laser power setting was tested on wooden boards derived from the same sheet in each repetition to ensure consistency and allow for comparative analysis. To ensure repeatability, all *Tapis* motifs were redrawn as vector artwork in CorelDRAW X8 (Corel Corp., Ottawa, Canada). The images were then exported in .cdr format. Due to the varying geometries of the motifs, line width was not standardised. Each file was subsequently imported into the CorelLaser application using the manufacturer's recommended settings to generate the engraving path and machine commands for the CO_2 laser system.

2.2.2. Color Change Testing

The color analysis of meranti wood was conducted before and after laser engraving using the Amtast AMT507 colorimeter. The evaluation of color changes ($\Delta L*$, $\Delta a*$, $\Delta b*$, $\Delta E*$) was performed based on the CIE-Lab color space system, which measures brightness ($L*$), red/green chromaticity ($a*$), and yellow/blue chromaticity ($b*$). The extent of color change, represented by $\Delta L*$, $\Delta a*$, $\Delta b*$, and

ΔE^*, was calculated using the following formula and subsequently interpreted by Table 1.

$$\Delta L^* = L^*_1 - L^*_0$$
$$\Delta a^* = a^*_1 - a^*_0$$
$$\Delta b^* = b^*_1 - b^*_0$$
$$\Delta E^* = (\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})^{1/2}$$

ΔL^*, Δa^*, and Δb^* represent the changes in L^*, a^*, and b^*, with subscripts 1 and 0 indicating measurements after and before engraving, respectively. These reflect shifts in brightness and red–green/yellow–blue chromaticity; ΔE^* indicates the overall color change—the greater the ΔE^*, the more noticeable the difference.

2.2.3. Consumer Preferences

Consumer preference data was collected through a questionnaire distributed to respondents using Google Forms. The selection of respondents targeted students from the University of Lampung, within the age range of 18–23 years, based on the assumption that this demographic represents the university's total student population of 22,262 (2021). Sampling was conducted randomly using the Slovin formula with a 10% margin of error and a 90% confidence level, as expressed in the following Formula 1.

$$n = \frac{N}{1 + N(e)^2} \qquad (1)$$

In the Formula 1, n is the required sample size (number of respondents), N is the population size, and e is the tolerated margin of error. With N = 22,262 and e = 0.10 at a 90% confidence level, the calculated n is approximately 100 respondents were selected for the study. Data collection involved interviews in which respondents were shown three different laser-engraved wood samples, each produced with varying laser power settings, to assess their preferences for the most visually appealing engraving results.

3. RESULTS AND DISCUSSIONS

3.1. Color Changes

The results indicated that variations in laser power significantly influenced the color changes in meranti wood before and after CO_2 laser engraving, as illustrated in Fig. 2. The most prominent visual change observed was a darkening of the wood or a reduction in brightness due to the thermal effect of laser engraving, a phenomenon commonly associated with burning or heat treatment [32]. The results demonstrated that increasing the laser power led to a darkening effect on Meranti wood, resulting in a decrease in L^* as shown in Fig. 3. Before laser treatment, Meranti wood exhibited a brownish color, which gradually darkened as the laser power increased. This observation aligns with the findings of Nugraha et al. [20], which indicate that low laser power is insufficient to fully burn the wood surface, resulting in only slight discoloration to a brown hue. Furthermore, the L^* value was significantly
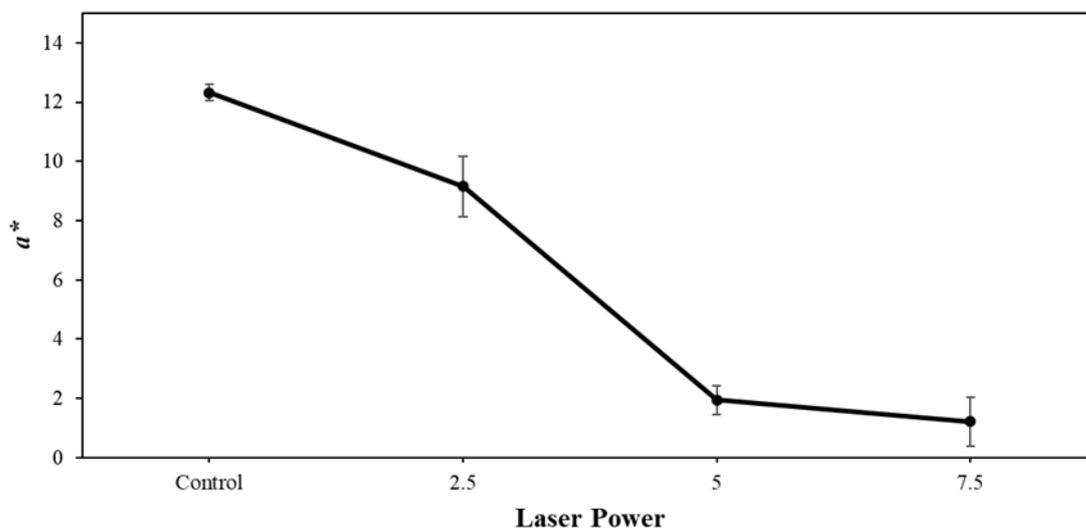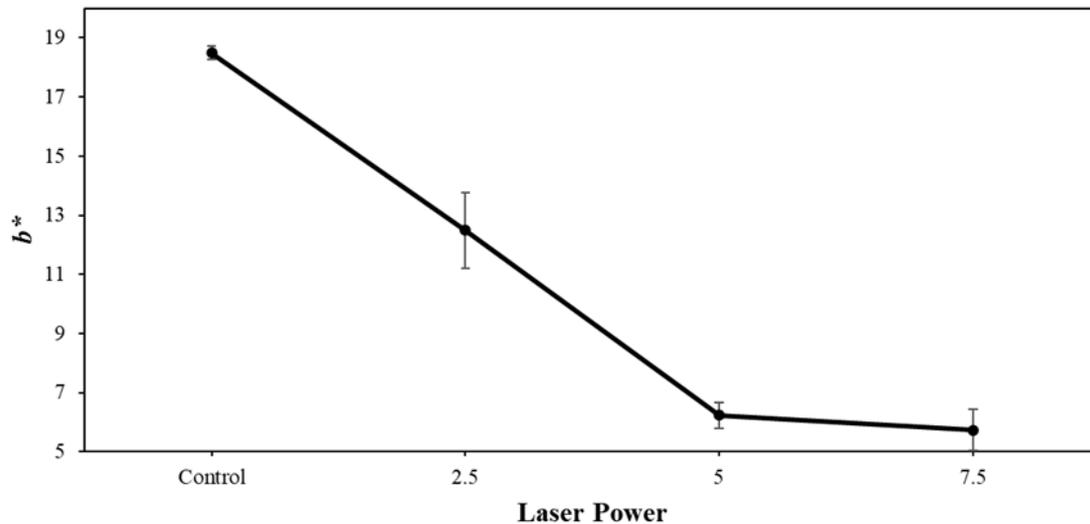

Figure 4. Effect of CO_2 laser power on red/green chromatization change (a^*).

Figure 5. Effect of CO_2 laser power on blue/yellow chromatization changes ($b*$).

Table 2. Color change ($\Delta E*$) of Meranti wood after CO_2 laser engraving.

Laser Power (Watt)	Total Color Change ($\Delta E*$)	Description
2.5	30.04 (1.99)	Total color change
5.0	42.52 (0.89)	Total color change
7.5	43.73 (1.29)	Total color change

reduced with higher laser power. In contrast, a faster cutting speed resulted in only a minor decrease. The color change observed is attributed to alterations in the chemical composition of the wood during the heating process [33].

The $a*$ (Fig. 4) and $b*$ (Fig. 5) chromaticity followed the same trend as $L*$, both decreasing with increasing laser power. This finding is consistent with the study conducted by Amany et al. [15], which reported a similar pattern of change in CO_2 laser engraving on particleboard. According to Kúdela et al. [34], the $a*$ and $b*$ values significantly decreased, approaching zero at the highest irradiation dose, indicating a shift towards green and blue. The observed color changes in the engraving process are primarily attributed to combustion on the wood surface, leading to the oxidation of hemicellulose and the formation of dark-colored compounds [35][36].

The $\Delta E*$ of Meranti wood is presented in Table 2. According to Chen and Wang [37], laser beam operating parameters, including laser power, movement speed, and radiation width, significantly influence the $L*$ and $\Delta E*$ color components. All measured $\Delta E*$ values were ≤12, indicating that the

laser engraving process resulted in a complete color transformation of Meranti wood across all applied power levels.

A visual comparison of Fig. 2 with the descriptive data in Table 2 shows a clear and consistent trend in all CIE-Lab coordinates as laser power increases. Raising the power from 2.5 to 5.0 W reduced the mean $L*$ value by approximately one-third, indicating a substantial darkening of the meranti wood surface. Increasing the power further to 7.5 W resulted in an additional, but smaller, decrease in $L*$, suggesting that the darkening effect begins to level off beyond approximately 5.0 W. The $a*$ coordinate shifted progressively toward positive values, indicating an enhancement of red tones often associated with the formation of carbonyl and quinone chromophores during the thermal modification of lignin-rich regions [38]. Concurrently, the $b*$ coordinate shifted toward negative values, reflecting a slight move toward greener hues, which aligns with the gradual breakdown of light-scattering hemicellulose components. Together, these changes produced $\Delta E*$ values exceeding the commonly accepted perceptibility threshold ($\Delta E* > 3$) at the

intermediate power level, confirming that even moderate laser intensities generate colour changes easily discernible to untrained observers [39]. Comparable monotonic trends—though at higher threshold powers—have been reported for beech [40] and oak [41], suggesting that such behaviour is typical of diffuse-porous hardwoods with moderate thermal diffusivity.

The ΔE^* values presented in Table 2 (30.04–43.73) are substantially higher than the human just-noticeable-difference threshold. Psychophysical studies on finished wood surfaces indicate that a colour difference becomes perceptible at approximately $\Delta E^* \approx 0.5$, while values near 2.0 are already perceived as "noticeable" hues [42]. Based on the classification scale in Table 1, all three power settings fall within the "total color change" category ($\Delta E^* > 12$), indicating a distinct and highly noticeable visual transformation. These considerable shifts are in line with previous findings on CO_2 laser treatments of beech and oak, where thermal degradation of hemicelluloses and chemical modifications of lignin produce new chromophores, resulting in surface darkening and elevating ΔE^* values to the upper range of perceptibility [40][41].

According to Hidayat et al. [43], heat treatment of wood surfaces results in a darkening effect. The color change observed during the engraving process is attributed to alterations in the chemical composition of the wood due to thermal degradation caused by laser exposure [44]. These color changes are a crucial consideration, as they can directly impact the economic value of the final product [13]. When the CO_2 laser heats the wood, it triggers a series of chemical reactions that gradually darken the surface. At lower heating temperatures (about 180–300 °C), the more heat-sensitive hemicelluloses break down, releasing water and producing small sugar-based compounds such as levoglucosan, along with furfural and 5-hydroxymethyl-furfural [45]. These substances can react further to form coloured compounds that give the surface its initial brown shade [46]. As the laser power increases, the lignin in the wood undergoes chemical changes, producing phenols and other aromatic compounds that link together to form dark, carbon-rich materials. At even higher temperatures (above about 350 °C), cellulose also begins to char, resulting in a nearly black surface, especially at 5.0–7.5 W [47].

This step-by-step process—from hemicellulose breakdown to lignin transformation and cellulose charring—creates the gradual colour change, showing that the effect is driven by specific chemical changes rather than simple burning. Practically, even the lowest tested power (2.5 W) produces a change that is immediately visible without the need for instrumentation, implying that any variations in laser parameters are likely to be observed by end-users and should therefore be precisely controlled in production processes. Based on the data presented in Table 2, the color difference between 5.0 and 7.5 W laser power is
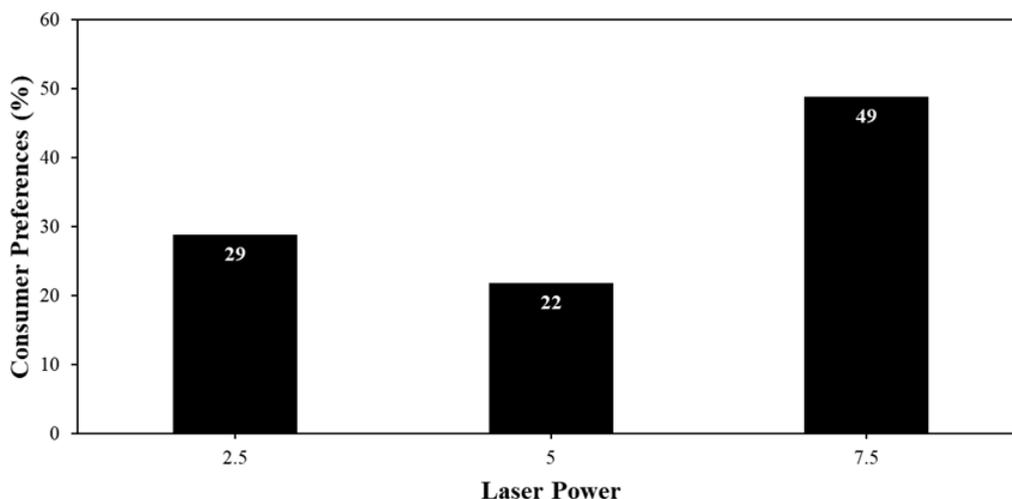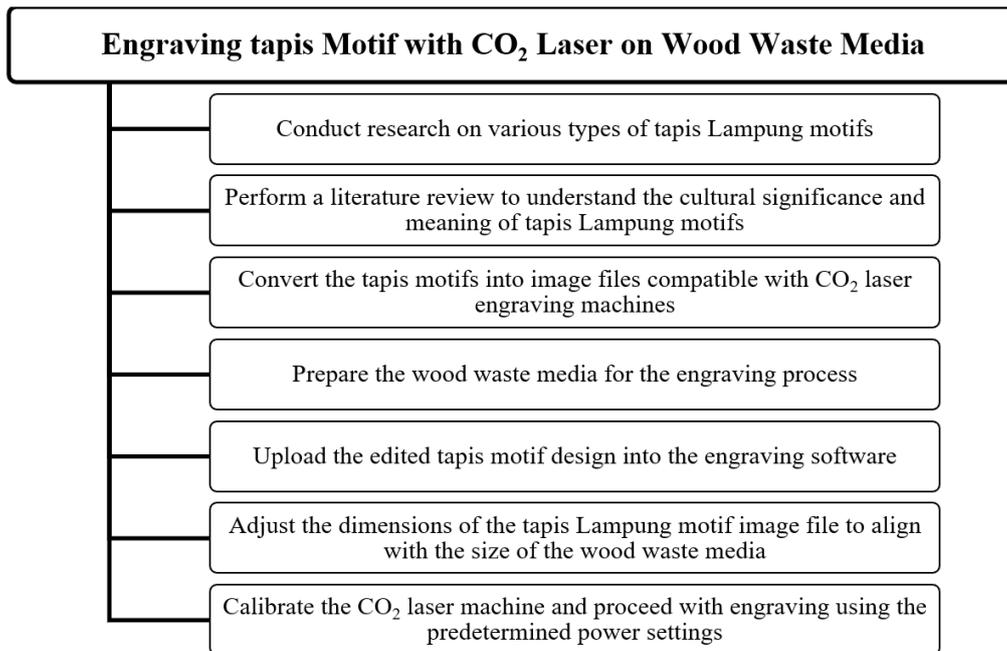

Figure 6. Consumer preference for the color of engraved Meranti wood.

Engraving tapis Motif with CO_2 Laser on Wood Waste Media

Conduct research on various types of tapis Lampung motifs

Perform a literature review to understand the cultural significance and meaning of tapis Lampung motifs

Convert the tapis motifs into image files compatible with CO_2 laser engraving machines

Prepare the wood waste media for the engraving process

Upload the edited tapis motif design into the engraving software

Adjust the dimensions of the tapis Lampung motif image file to align with the size of the wood waste media

Calibrate the CO_2 laser machine and proceed with engraving using the predetermined power settings

Figure 7. Stages of wood engraving using a CO_2 laser.

minimal. However, as laser power increases, energy consumption also rises. Therefore, it can be concluded that 5.0 W is the most efficient power setting, as it achieves a similar color effect to 7.5 W while consuming less energy.

The stronger development of darker hues at higher laser powers is primarily attributed to the progressive devolatilization and surface condensation of lignin-derived phenolic compounds, which function as chromophores [43]. In this study, the power threshold for achieving a "total color change" appearance (≥ 2.5 W) was lower than the 12 W threshold reported for beech [40], highlighting the influence of species-specific thermal properties on colour transformation. Although the monotonic decrease in $L*$ accompanied by consistent shifts in $a*$ and $b*$, confirms effective surface darkening, certain practical limitations must be acknowledged. In this study, the boards were pre-conditioned to a moisture content of $\pm 15\%$. Higher moisture content levels increase the wood's heat absorption capacity and are likely to reduce colour uniformity, as reported in previous work on redwood engraved under uncontrolled ambient humidity [48]. Therefore, future investigations should establish moisture-specific parameter settings to ensure consistent chromatic results under industrial production conditions.

3.2. Consumer Preferences

Consumer preference data is a crucial consideration for decision-makers in the forestry sector, providing valuable insights into market demand for wood products [49]. This study examines consumer preferences, which play a crucial role in decision-making during production by offering information on market trends and consumer expectations [43]. Among the various attributes influencing consumer choices, color is a significant factor in selecting wood products [50]. Based on interviews conducted with 100 respondents, Meranti wood engraved at the highest laser power level received the most consumer interest compared to lower power levels (Fig. 6). Although the 7.5 W setting received the highest preference (49%), its visual advantage over the 5 W treatment is smaller than it might seem. Increasing the power from 5.0 to 7.5 W reduced $L*$ by only about one point (Fig. 3) and increased $\Delta E*$ by just 1.21 (Table 2). On the CIE-Lab perceptibility scale, an $\Delta E*$ below 1.5 is considered "slightly perceivable", meaning most people would barely notice the change under normal lighting. In other words, the extra 2.5 W—representing a 50% increase in energy—produces only a minimal difference for the average viewer.

Previous psychophysical research has shown that

darker brown-to-black tones are often associated with higher material value, durability, and a "premium" appearance in hardwood products [43] [51]. The stronger carbonisation resulting from higher laser power can also produce a glossier, more uniform surface, which may be perceived as an intentional finishing treatment rather than incidental scorching [52]. Similar trends have been observed in other species, where darker and more uniform surfaces were rated as smoother and better crafted, even when objective surface roughness showed no further improvement beyond a moderate power setting [19].

From a production perspective, the higher energy demand of the 7.5 W setting carries both economic and environmental implications, as laser power is a primary driver of electricity consumption in CO_2 systems. Since the 5.0 W treatment already achieves a "total color changed" colour state ($\Delta E^* > 12$) and satisfies perceptual thresholds for most consumers, it offers a practical balance between visual quality and sustainability. The 7.5 W setting may be reserved for specialized or premium applications requiring maximum contrast. In comparison, the 5.0 W setting can be adopted for large-scale production to minimize energy use and associated CO_2 emissions.

Integrating market perception with processing outcomes, the preference data in this study align with broader consumer trends favouring darker, more carbonised wood tones, as reported in recent retail surveys for heat-treated hardwoods [41]. Nevertheless, the ~50% increase in power required to move from 5.0 to 7.5 W—resulting in only a marginal and barely perceptible additional darkening ($\Delta E^* \approx 1.2$) underscores a clear optimisation opportunity. Laser powers in the range of 5–6 W appear to provide an effective balance between aesthetic appeal and energy efficiency. This finding underscores the importance of integrating consumer preference data with objective colour science metrics when optimising laser parameters for heritage-oriented wood products.

3.3. CO_2 Laser Application on Tapis Motifs

Laser has distinctive and unique characteristics compared to other rays. The characteristics of different laser types, such as wavelength, output, and beam profile, vary, resulting in distinct strengths and weaknesses [17]. The CO_2 laser has several advantages compared to other laser types, including high beam accuracy and high power output, which accounts for 5–20% of the total power used to produce light. They can engrave with precision on even the smallest details. This is a high value compared to other types of gas lasers. CO_2 laser emits wavelengths between 9–11 μm, which can be used for organic materials such as wood and ceramics [16]. Based on the findings of this study, the application of CO_2 laser technology for preserving *Tapis* motifs is most effective when using wood waste with naturally bright to moderately dark colors, ensuring high contrast in the engraving results. The optimal laser power used in this study was 7.5 W, producing a darker engraving preferred by consumers while maintaining energy efficiency [14]. The engraving process involved several stages: first, preparing the *Tapis* design for laser engraving and adjusting the design dimensions to fit the wood-waste medium; the engraving apparatus and sample positioning are
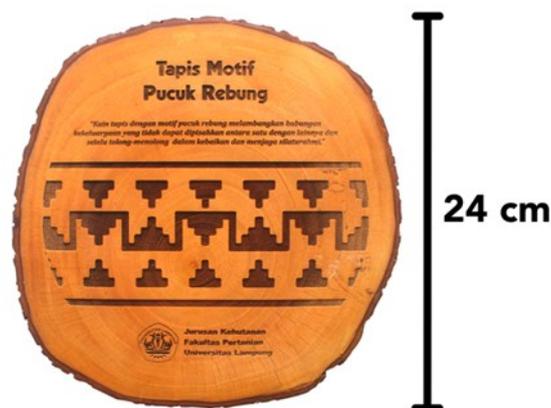

Figure 8. Engraving of the *Tapis Pucuk Rebung* motif.

Figure 9. Engraving of the *Tapis Kapal* motif.

shown in Fig. 7. Finally, engraving was performed using the predetermined laser-power settings (Fig. 6). The resulting engraved *Tapis* motifs are illustrated in Fig. 8 – 10.

The selection of the 7.5 W setting for engraving was based on the color change and perception results presented in Sections 3.1 and 3.2, respectively. At this power level, meranti wood surfaces achieved an L^* value of 32.03 and ΔE^* of 43.73, producing the darkest and most visually contrasting background among the tested settings. These characteristics were strongly favoured by respondents, with 49% selecting the 7.5 W sample as the most appealing (Fig. 6). Applying this parameter in the cultural engraving tests ensured that the Pucuk Rebung, Kapal, and Jung Sarat motifs (Fig. 8 – 10) were rendered with a consistently dark tone and distinct separation between engraved and non-engraved areas. The 7.5 W setting also preserved the fine chevron geometry of Pucuk Rebung and the intricate narrative detailing of Kapal and Jung Sarat, ensuring that their cultural and artistic value was retained in the engraved form. Comparable studies on beech and oak have shown that moderate-to-high CO_2 laser powers (>5 W) promote controlled carbonisation, enhancing the clarity and legibility of engraved patterns. In this study, the use of 7.5 W produced motif details with high visual definition, aligning with both quantitative colourimetry results and user preferences, thereby validating the techno-aesthetic workflow outlined in Fig. 7. The *Pucuk Rebung* motif symbolizes the inseparable bonds of family relationships. It emphasizes the importance of mutual support within the family and open communication to address mistakes, preventing disputes and misunderstandings in familial interactions [3].

The *Kapal* motif holds profound significance for the people of Lampung in ancient times, symbolizing the deceased's spiritual journey to the afterlife. This motif often incorporates dark colors and represents a narrative divided into three realms: the human world, the upper world (heaven), and the lower world (the underworld). However, with the influence of external cultures entering the Lampung region, the meaning of the Kapal motif has experienced a shift over time [1]. The *Jung Sarat* motif (Fig. 10) is a combination of several other motifs, such as *Pucuk Rebung*, *Belah Ketupat*, *Sasab*, and *Tajuk Dipergaya*. Each of these motifs has its meaning. For instance, the *Tajuk Dipergaya* motif represents the need to adapt easily but with dignity to the surrounding social environment (*Piil Pesenggiri*). The motif of *Belah Ketupat* reflects the value of good behavior and good deeds for the sake of all. The *Sasab* motif, on the other hand, denotes possession of useful knowledge [53].

This study focused on a single tropical hardwood tested at three different power levels, emphasizing color change rather than surface chemistry and mechanical performance. Since laser–wood interactions depend on factors like density, early- and latewood contrast, and extractive content, the quantitative power–color relationships presented here should not be considered universally applicable yet. Future research should (i) broaden the scope to include both ring-porous and diffuse-porous temperate species, (ii) combine colorimetric measurements with spectroscopic mapping to examine chemical gradients below the irradiated surface, and (iii) evaluate coating adhesion and

weathering resistance of engraved substrates. These findings will be essential for supporting the integration of CO_2 laser engraving into sustainable production workflows that not only ensure the high-fidelity preservation of *Tapis* motifs but also promote the utilisation of wood waste as a long-term carbon storage medium. By embedding traditional designs onto repurposed lignocellulosic material, this approach contributes to cultural heritage conservation while aiding in greenhouse gas mitigation through extended carbon sequestration.

4. CONCLUSIONS

This study demonstrates that CO_2 laser engraving on wood waste offers an innovative, creative, and functional approach for preserving and promoting the *Tapis* motif. Quantitative analysis confirmed significant and measurable color changes on meranti wood, with notable reductions in brightness (L^*) and chromatic coordinates (a^*, b^*), along with increases in total color difference (ΔE^*), reaching the "total color change" range ($\Delta E^* \approx$ 30.04–43.73). These results indicate strong and durable visual contrast suitable for precise motif reproduction. Consumer preferences analysis revealed that 49% of respondents favored the darkest engraving (7.5 W). However, the 5.0 W setting produced a similar appearance with lower energy consumption, making it a practical balance between aesthetics and sustainability. The study was limited to meranti wood, with fixed engraving parameters and a moisture content within ±15%; the effects of different species, moisture levels, and laser speed remain untested and could influence the outcomes. The darkening mechanism—caused by hemicellulose depolymerization, lignin modification, and cellulose charring—also requires further research regarding its effects on emissions, coating adhesion, and durability. Recommendations include using 5.0 W as the standard setting and reserving 7.5 W for premium pieces, expanding trials to various species and conditions, combining colorimetry with spectroscopic and weathering tests, and conducting energy, emissions, and life-cycle assessments through pilot-scale trials. Integrating these improvements into local cultural production can enhance heritage preservation, increase economic value, and support carbon sequestration by transforming wood waste into durable artworks.

AUTHOR INFORMATION

Corresponding Author

Wahyu Hidayat — Department of Forestry, University of Lampung, Bandar Lampung-35141 (Indonesia);
ⓘ orcid.org/0000-0002-6015-1623
Email: wahyu.hidayat@fp.unila.ac.id

Authors

Bagus Saputra — Department of Environment and Forest Resources, Chungnam National University, Daejeon-34134 (Republic of Korea); Clean Air Research Laboratory, Korea Institute of Energy Research, Daejeon-34129 (Republic of Korea);
ⓘ orcid.org/0009-0000-4378-1853
Alim Fadila Rahman — Department of Forestry, University of Lampung, Bandar
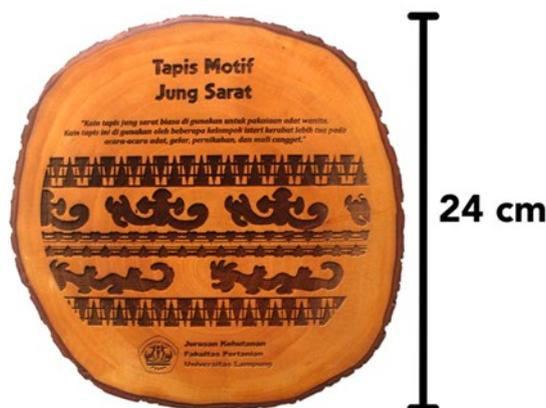
Figure 10. Engraving of the *Tapis Jung Sarat* motif.

Lampung-35141 (Indonesia);

 orcid.org/0009-0004-1042-5368

Intan Fajar Suri — Department of Forestry, University of Lampung, Bandar Lampung-35141 (Indonesia);

 orcid.org/0000-0003-4091-4010

Indra Gumay Febryano — Department of Forestry, University of Lampung, Bandar Lampung-35141 (Indonesia);

 orcid.org/0000-0001-7242-656X

Duryat Duryat — Department of Forestry, University of Lampung, Bandar Lampung-35141 (Indonesia);

 orcid.org/0009-0001-8652-4352

Dian Iswandaru — Department of Forestry, University of Lampung, Bandar Lampung-35141 (Indonesia);

 orcid.org/0000-0001-8837-0126

Author Contributions

Conceptualization and Supervision, W. H. and I. G. F.; Methodology and Writing – Original Draft Preparation, W. H. and B. S.; Software, A. F. R. and D. I.; Validation, W. H. and D. D.; Formal Analysis, A. F. R. and I. F. S.; Investigation, Data Curation, and Visualization, B. S. and A. F. R.; Resources, D. D. and D. I.; Writing – Review & Editing, W. H. and I. F. S.; Project Administration, I. F. S.; Funding Acquisition, W. H.

Conflicts of Interest

The authors declare no conflict of interest.

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DECLARATION OF GENERATIVE AI

Not applicable.

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PANDAWA
INSTITUTE