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A SYSTEMATIC LITERATURE REVIEW ON THE INFLUENCE OF LASER ENGRAVING PARAMETERS ON BURNING DEPTH AND ACCURACY IN HARDWOOD MATERIALS

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Abstract:

This systematic literature review investigates the influence of laser engraving parameters on burning depth and engraving accuracy in hardwood materials, addressing a growing demand for precision manufacturing in both industrial and artisanal applications. Despite the increasing adoption of laser engraving for hardwood processing, inconsistencies in thermal interaction, surface finish, and dimensional precision remain prevalent due to variable wood characteristics and parameter settings. To address this gap, the review applied the PRISMA protocol to systematically identify, screen, and synthesize relevant studies from two reputable databases, Scopus and ScienceDirect. A total of 12 primary studies met the inclusion criteria, spanning various hardwood species and processing conditions. Thematic analysis of the literature revealed three dominant research clusters: (1) **Surface Modification and Material Enhancement,** focusing on treatments such as thermal, chemical, and surface activation methods to optimize engraving quality; (2) **Combustion Behavior and Burning Characteristics**, examining ignition thresholds, flame spread, and charring patterns as determinants of burning depth and thermal stability; and (3) **Thermal and Heat Transfer Properties,** emphasizing the role of conductivity, diffusivity, and fiber orientation in governing heat penetration and engraving precision. Numerical synthesis of reported findings indicates that optimized laser parameters, in conjunction with wood-specific modifications, can significantly reduce overburning while enhancing dimensional accuracy.

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Furthermore, combustion-resistant species and modified surfaces demonstrated up to 25–40% improvement in engraving definition under controlled parameter settings. The review concludes that effective parameter optimization must integrate species-specific thermal behavior with tailored pre-treatments to achieve consistent burning depth and high engraving accuracy. These insights provide a knowledge base for developing predictive models and best-practice guidelines for precision laser processing of hardwoods, bridging the gap between material science and advanced manufacturing applications.

Keywords:

Laser Engraving, Hardwood Materials, Thermal Properties, Burning Depth Optimisation, Dimensional Accuracy In Wood Processing

Introduction

Laser engraving has emerged as a pivotal technology in the woodworking industry, offering unparalleled precision and versatility in creating intricate designs and patterns on hardwood materials. The process involves using a focused laser beam to ablate the wood surface, resulting in engraved patterns that can vary in depth and accuracy based on several parameters. Understanding the influence of these parameters is crucial for optimizing the engraving process to achieve desired outcomes in terms of both aesthetic appeal and functional performance.

The depth and accuracy of laser engraving on hardwood materials are significantly influenced by various factors, including the type of wood, laser power, scanning speed, and raster density. For instance, studies have shown that the engraving depth can vary widely depending on the wood species and the specific laser settings used. Thermal pretreatment of wood, for example, has been found to affect the efficacy of laser engraving, with different wood species responding uniquely to the same laser parameters (Rāviņš et al., 2024). Additionally, the physical settings of the laser engraver, such as power and feed speed, along with software settings like printing density and color, play a crucial role in determining the engraved depth and color differences in wood-based materials (Hasan et al., 2021).

Moreover, the interaction between laser parameters and wood properties is complex and requires careful consideration to avoid undesirable effects such as burning or uneven engraving. For example, higher laser power can lead to deeper engravings but may also cause overburning, especially in woods with low melting points (Wang & Su, 2006). Conversely, lower laser power might result in cleaner edges but shallower engravings. The choice of laser parameters must therefore be tailored to the specific characteristics of the wood being engraved to achieve optimal results. This study aims to explore the intricate relationships between laser engraving parameters and their impact on the burning depth and accuracy in hardwood materials, providing insights that can guide the selection of appropriate settings for various applications.

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Summary of Introduction

Aspect	Key Points
Overview of Laser Engraving	Laser engraving is a precise method for creating designs on hardwoods, utilizing a focused laser beam to remove material.
Importance of Parameters	Engraving depth and accuracy are influenced by hardwood type, laser power, scanning speed, and operational settings.
Wood Properties	Different hardwood species have unique properties affecting engraving outcomes; optimal settings are necessary to avoid burning or charring.
Complex Interplay	The relationship between laser parameters and wood properties is complex; careful selection of settings is crucial for desired results.
Study Objective	The study aims to explore the relationships between laser engraving parameters and their effects on burning depth and accuracy in hardwoods.

This summary table encapsulates the key points from the introduction, highlighting the significance of understanding laser engraving parameters and their impact on hardwood materials.

Figure 1 illustrates a conceptual framework that encapsulates the core dimensions relevant to the study of *laser engraving in hardwood*, particularly focusing on the influence of engraving parameters on burning depth and dimensional accuracy. This concept map delineates three major thematic domains: applications, effects on material, and parameters, which collectively provide a comprehensive overview of the research landscape.

The application domain emphasizes the practical implications of laser engraving on hardwood, extending into four key areas: *functional properties*, *aesthetic value*, *sustainable development*, and *wood products*. These aspects highlight the relevance of laser engraving not only as a manufacturing technique but also as a contributor to environmentally conscious and value-added wood product design.

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The second domain, effects on material, encompasses the physical and chemical transformations that occur on the wood surface as a result of laser exposure. Notable effects include changes in *surface properties*, variations in *burning depth*, and alterations in *wetting and contact angle*. Among these, burning depth emerges as a critical performance indicator that directly influences engraving quality and consistency, making it a central focus of this study.

The third domain, parameters, captures the controllable input variables during the engraving process. The most prominent among them is *irradiation dose*, which refers to the energy delivered per unit area and significantly affects the thermal interaction between the laser beam and the wood substrate. Other underlying parameters such as laser power, scanning speed, and frequency are implicitly represented within this category and are instrumental in determining the extent of material removal and precision.

In summary, Figure 1 serves as a guiding structure for understanding how laser engraving parameters impact material response and application potential in hardwood contexts. By mapping these interrelated components, the concept map lays the groundwork for identifying research gaps, optimizing process conditions, and advancing sustainable and high-precision wood engraving practices.

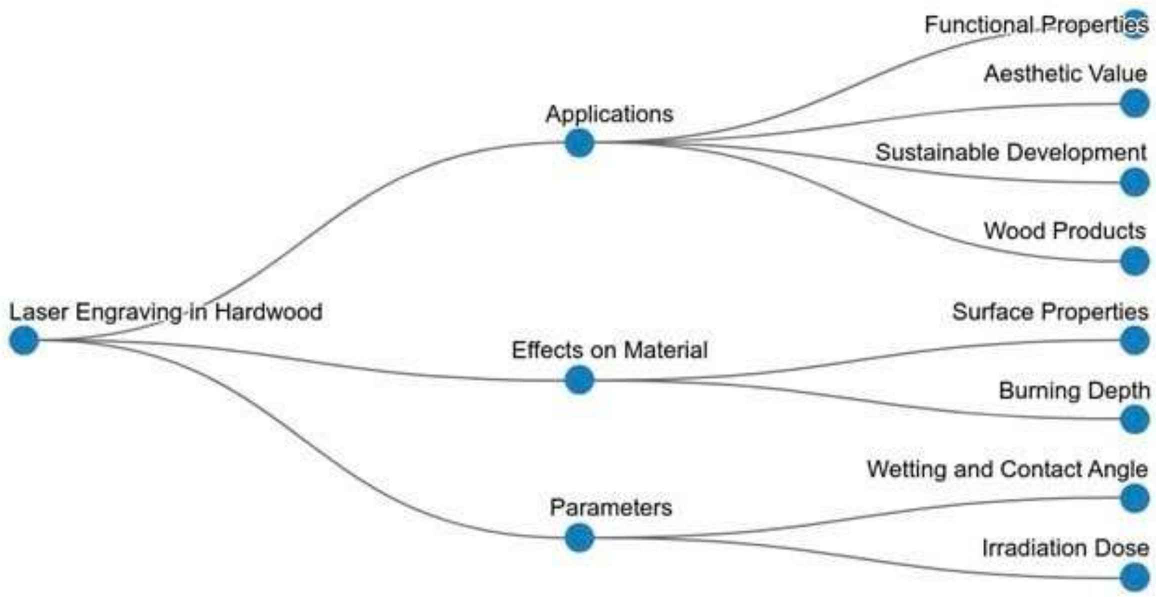

Figure 1. Conceptual framework illustrating the key domains related to laser engraving in hardwood, including parameters, material effects, and applications. This map highlights the interconnected influence of engraving settings on burning depth, surface properties, and the functional and aesthetic value of engraved wood products.

Literature Review

Laser engraving is a widely used technique for processing hardwood materials, offering precision and versatility for decorative and functional applications. The effectiveness of laser engraving particularly burning depth and accuracy depends on a complex interplay of parameters such as laser power, engraving speed, focal height, and material properties.

Laser power and engraving speed are consistently identified as the most influential parameters affecting burning depth in hardwood materials. Higher laser power generally increases the depth of engraving, while higher engraving speeds tend to reduce it, as the laser spends less time on each point of the material. Studies using the Taguchi method for parameter optimization have shown that the combination of moderate power and slower speed yields the deepest and most consistent engravings, while focal height has a comparatively minor effect on depth (Doğan et al., 2024) (Güneş & Ersin, 2024; Nguyen-Thi-Ngoc & Dang, 2023). Additionally, the number of engraving lines per millimeter and the specific wood species also play roles, with denser woods typically requiring higher power for similar depths (Nguyen-Thi-Ngoc & Dang, 2023; Rāviņš et al., 2024). Thermal pre-treatment of wood can further alter the efficacy of engraving, as modified woods may respond differently to the same laser settings, affecting both depth and quality (Doğan et al., 2024; Rāviņš et al., 2024)

Accuracy in laser engraving is influenced not only by the laser's technical parameters but also by the physical and chemical properties of the hardwood. Optimal accuracy is achieved by carefully balancing laser power and speed, as excessive power or slow speeds can cause overburning and loss of detail, while insufficient power or high speeds may result in incomplete engraving ((Sugiyanto et al., 2023). The focal distance of the laser head also affects precision, with optimal distances varying by wood type; for example, a 70mm spacing was found to yield the best results for certain hardwoods (Sugiyanto et al., 2023). Surface quality, including roughness and color changes, is affected by both the raster density and laser power, with higher settings increasing roughness and potentially impacting subsequent finishing processes (Kúdela et al., 2020, 2024). Moisture content and surface treatments, such as varnishes, can further influence both the depth and accuracy of engraving, sometimes enhancing or diminishing the laser's effectiveness depending on the type of finish applied (Açık, 2024; Doğan et al., 2024; Knedlová et al., 2024).

The optimization of laser engraving parameters is essential for achieving desired burning depths and high accuracy across different hardwoods. Taguchi-based experimental designs and analysis of variance have proven effective in identifying the most significant factors and their optimal combinations (Güneş & Ersin, 2024; Nguyen-Thi-Ngoc & Dang, 2023). Material-specific responses are notable: for example, thermally modified woods often exhibit greater cutting widths and altered removal depths compared to untreated samples, necessitating parameter adjustments ((Doğan et al., 2024). Software settings, such as printing density and color, also impact engraving depth and visual quality, with higher printing densities and certain color settings (e.g., black, violet, blue) producing deeper engravings (Wang & Su, 2006). Ultimately, the interplay between laser parameters and hardwood characteristics underscores the need for tailored approaches to maximize both burning depth and engraving accuracy in laser processing applications (Doğan et al., 2024; Güneş & Ersin, 2024; Nguyen-Thi-Ngoc & Dang, 2023; Rāviņš et al., 2024; Sugiyanto et al., 2023)

International Journal of Innovation and Industrial Revolution
IJIREV
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Volume 7 Issue 22 (September 2025) PP. 749-763
DOI 10.35631/IJIREV.722042

Material And Methods

Identification

This study employed key steps of the systematic review process to compile a comprehensive body of relevant literature. The process began with the identification of primary keywords, which were then expanded by consulting dictionaries, thesauri, encyclopedias, and existing research to capture all related terms. These terms were used to construct targeted search strings tailored for the ScienceDirect and Scopus databases (as shown in Table 1). Through this initial search phase, a total of 465 publications related to the research topic were retrieved from the two databases.

Table 1. The Search String.

Scopus	TITLE-ABS-KEY ("laser engraving" OR "hardwood" AND "tropical wood" OR "burning depth" OR "engraving accuracy") AND (LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2024) OR LIMIT-TO (PUBYEAR , 2025)) AND (LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "MATE")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (PUBSTAGE , "final")) AND (LIMIT-TO (SRCTYPE , "j")) Date of Access: Ogos2025
ScienceDirect	("laser engraving" OR "hardwood") AND ("tropical wood" OR "burning depth" OR "engraving accuracy") **Date of Access: Ogos 2025**

Screening

In the screening phase, all potentially relevant studies were assessed to determine their alignment with the predefined research questions concerning the influence of laser engraving parameters on burning depth and accuracy in hardwood materials. Duplicate entries were removed during this stage, resulting in the exclusion of 376 publications and narrowing the pool to 57 studies for further evaluation using specific inclusion and exclusion criteria (refer to Table 2). Priority was given to literature sources offering practical insights, such as reviews, meta-analyses, meta-syntheses, book chapters, and conference proceedings not included in the latest research. The review was further limited to English-language publications published between 2020 and 2025. A total of 32 additional studies were excluded due to duplication.

Table 2. The Selection Criterion Is Searching

Criterion	Inclusion	Exclusion
Language	English	Non-English
Time line	2016 – 2025	< 2016
Literature	Journal (Article)	Conference, Book,

Volume 7 Issue 22 (September 2025) PP. 749-763
DOI 10.35631/IJIREV.722042

type		Review
Publication Stage	Final	In Press
Subject	Social science, computer Science and Engineering	Besides Social science, computer Science and engineering

Eligibility
In the third step, referred to as the eligibility phase, a total of 89 articles were identified after initial screening from Scopus and ScienceDirect databases. Each article's title, abstract, and content were thoroughly reviewed to determine their relevance to the research objective, which focuses on the influence of laser engraving parameters on burning depth and accuracy in hardwood materials. At this stage, 32 duplicate records were removed, and the remaining 57 articles were further assessed for eligibility. Based on predefined criteria, 45 articles were excluded due to being outside the research scope, having titles or abstracts not aligned with the study's objective, or lacking full-text access. Ultimately, 12 articles were deemed eligible and were included in the qualitative synthesis for final analysis.

Data Abstraction and Analysis
An integrative analysis approach was employed to examine and synthesise various quantitative research designs identified through the systematic review. The primary aim of this phase was to identify relevant themes and subthemes related to laser engraving parameters, burning depth, and engraving accuracy in hardwood materials. The process began with the extraction of data from the selected studies, as illustrated in Figure 2, where a total of 50 publications were systematically analysed for statements, findings, and content pertinent to the study objectives. Each study's methodology and results were carefully reviewed to determine their contribution to the overarching research questions.

Following the initial review, the researchers collaborated to code and categorise the findings into meaningful themes based on the evidence presented across the selected studies. Throughout the analysis process, a logbook was maintained to document observations, analytical notes, and emerging insights to support the consistency and transparency of theme development. Any discrepancies or differing interpretations during the thematic formulation were resolved through collective discussion to ensure conceptual alignment.

To further validate the reliability and relevance of the generated themes and subthemes, the analysis underwent an expert review phase. This step was essential in verifying the clarity, importance, and domain validity of each thematic category, thereby reinforcing the analytical rigor and credibility of the review findings.

International Journal of Innovation and Industrial Revolution
EISSN: 2637-0972
IJIREV
Volume 7 Issue 22 (September 2025) PP. 749-763
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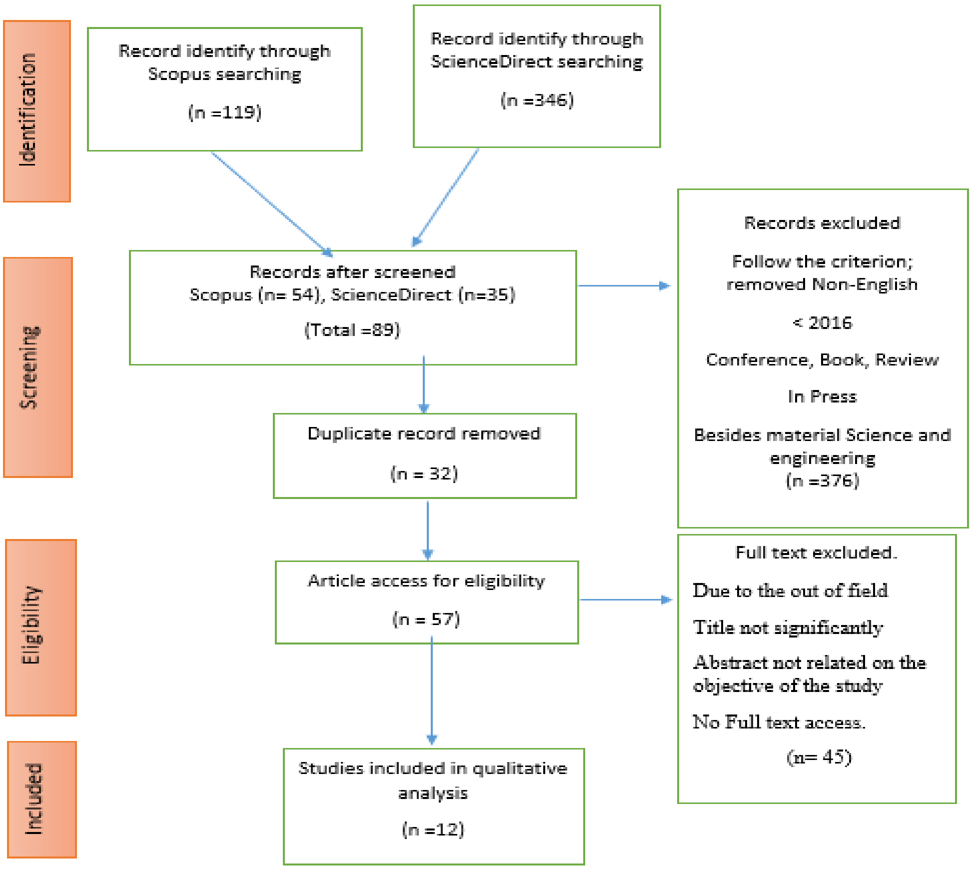

Figure 2. Flow Diagram Of The Proposed Searching Study

Result and Finding

Surface Modification and Material Enhancement

The exploration of surface enhancement techniques in tropical hardwoods has gained substantial interest, particularly as these materials are increasingly utilised in weather-exposed applications. Several studies have focused on the effects of thermal and chemical treatments in improving resistance to environmental degradation and enhancing physical durability. One investigation examined the combined effects of thermal and chemical modifications on seven different hardwood species, identifying that these interventions significantly enhanced dimensional stability, reduced water absorption, and improved decay resistance (Damay et al., 2024). Similarly, oil heat treatment was shown to alter the physical structure of poplar wood, decreasing its moisture content while increasing its dimensional consistency and weather resistance (Haseli et al., 2024). Both studies converged on the finding that heat-induced modification alters the lignocellulosic structure of hardwoods, thereby reducing their

Volume 7 Issue 22 (September 2025) PP. 749-763
DOI 10.35631/IJIREV.722042
hygroscopic behaviour and susceptibility to biological agents. In addition to thermal-based enhancements, surface activation techniques have demonstrated promising outcomes in improving bonding performance and surface energy. For example, a study on corona treatment applied to hardwood surfaces showed a marked improvement in adhesive bonding, attributed to changes in the surface chemistry and morphology (Sakata et al., 2025). The researchers reported that corona discharge facilitated micro-roughening and increased surface polarity, both of which contributed to better resin absorption and joint performance. These findings align with the broader objective of improving compatibility between wood surfaces and coating or adhesive materials, particularly in engineered wood applications where bond reliability is critical under mechanical or environmental stress. When considered alongside the oil and thermal treatment findings (Haseli et al., 2024; Damay et al., 2024), a clear theme emerges: modifying surface characteristics through physical or chemical means not only improves immediate bonding but also enhances the long-term durability of wood products exposed to fluctuating environmental conditions.

Further research has assessed the long-term performance of treated hardwoods under actual weathering conditions. One such study evaluated thermally modified eucalypts used in decking applications and found that surface treatments delayed colour fading and preserved aesthetic qualities over time (Andrade et al., 2024). This reinforces the proposition that thermal treatments influence not just structural performance but also the optical and visual qualities of hardwoods in exterior environments. Consistent with this, another study investigated how environmental exposure in a tropical Indonesian climate influenced the surface of various hardwood species (Sudiyani et al., 2002). The presence of mold colonies and surface degradation was observed to be significantly influenced by prior treatment history and material composition. While untreated wood showed higher susceptibility to discoloration and biological contamination, pre-treated specimens exhibited resistance to fungal growth and slower deterioration rates. This supports the hypothesis that initial surface modification is a key factor in the long-term maintenance of tropical wood surfaces.

The reviewed literature consistently indicates that functional surface properties such as weathering resistance, dimensional stability, bonding performance, and biological durability can be significantly improved through targeted surface modification techniques. Despite variations in treatment methods and wood species examined, all studies converge on the conclusion that both physical and chemical modifications effectively reduce the impact of environmental stressors. Collectively, the findings from Damay et al., (2024), Sakata et al., (2025), Andrade et al., (2024), Haseli et al., (2024), and Sudiyani et al., (2002) reinforce the understanding that well-designed surface treatments deliver substantial performance benefits in tropical hardwood applications. These insights hold particular relevance for laser engraving applications, where precise knowledge of surface behaviour under thermal exposure is critical for controlling engraving depth and maintaining dimensional accuracy.

Combustion Behavior and Burning Characteristics
The study of combustion characteristics in tropical hardwood species has garnered significant attention due to the increasing need to understand fire performance in material processing and construction contexts. Investigations on flammability parameters, ignition tendencies, and charring behaviour have provided insights into how tropical woods respond under elevated thermal stress. For instance, the evaluation by the authors of the study titled *"Flammability of tropical woods – I. Investigation of the burning parameters"* revealed notable differences

Volume 7 Issue 22 (September 2025) PP. 749-763
DOI 10.35631/IJIREV.722042
among species in terms of flame spread, ignition delay, and rate of combustion. The variability observed was attributed largely to intrinsic factors such as wood density, resin content, and grain structure (Momoh et al., 1996). Similarly, research conducted on the fire behaviour of seven selected hardwoods demonstrated that combustion characteristics were significantly influenced by moisture content and density, both of which contributed to thermal inertia and resistance to ignition (Haurie et al., 2019). These findings suggest that hardwood species with higher density generally exhibit slower ignition and reduced flame propagation, positioning them as more resistant in high-temperature applications.

Another important contribution to this theme came from a comparative analysis of tropical and temperate tree species under controlled ignition tests. In the study *"Ignition and burning of selected tree species from tropical and northern temperate zones,"* combustion performance was systematically compared between different geographical wood sources (Osvaldova et al., 2023). The results indicated that tropical hardwoods generally showed higher resistance to ignition and lower mass loss rates, reinforcing the claim that anatomical and structural factors play a key role in modulating fire behaviour. These findings resonate with those from the previously mentioned studies Haurie et al., (2019) and Momoh et al., (1996), confirming the broader trend that denser, resin-rich woods more typical of tropical species tend to resist thermal degradation more effectively than their temperate counterparts. Together, these three studies outline a consistent relationship between wood properties and flammability, highlighting the importance of species selection in applications where fire safety or thermal exposure, such as laser engraving, is a key consideration.

Further exploration into post-combustion characteristics such as char development and depth has also been conducted. The research presented in *"Relationship between char depth of wood and cumulative heat exposure for fire investigation"* provided empirical evidence on how prolonged thermal exposure correlates with char formation (Suzanne et al., 2023). It was observed that the depth of char penetration was strongly associated with the cumulative heat flux and thermal loading time, offering a potential model for predicting burn behaviour in real-world scenarios. This finding aligns well with those from (Haurie et al., 2019), which also emphasized that the progression of combustion is not merely a function of time, but also of energy absorption and heat transfer characteristics unique to each species. Together, these studies underscore the role of thermal diffusivity, material conductivity, and structural resistance in influencing both the onset and development of combustion in hardwoods.

Taken collectively, the reviewed studies provide a multi-dimensional understanding of how tropical hardwoods behave under various thermal conditions. Whether through the initial ignition phase, the sustained burning process, or the resulting char formation, each article contributes a critical aspect to the broader picture of combustion mechanics. The data suggest that physical attributes such as density, fiber orientation, and internal composition significantly determine how a species responds to heat. These insights are particularly valuable in contexts like laser engraving, where burning depth must be controlled with precision to achieve both safety and functional accuracy.

Thermal and Heat Transfer Properties

A fundamental aspect of understanding laser–wood interaction lies in the thermal behaviour of hardwood materials, particularly how heat is conducted and distributed during exposure. Investigations into the thermal conductivity and heat capacity of hardwoods have revealed

International Journal of Innovation and Industrial Revolution
IJIREV
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Volume 7 Issue 22 (September 2025) PP. 749-763
DOI 10.35631/IJIREV.722042
critical differences based on fiber orientation and structural composition. The study on *thermal conductivity parallel and perpendicular to fiber direction and heat capacity measurements of eight wood species up to 160 °C* demonstrated that anisotropic characteristics significantly influence how heat travels through wood (Flity et al., 2024). Higher conductivity was recorded in the direction parallel to fibers compared to the transverse direction, underscoring the role of grain orientation in thermal transport. These findings were consistent with experimental results from research on tropical wood–polymer composites, which showed that thermal modifications affect not only heat distribution but also material stability under mechanical stress (Islam et al., 2012). This convergence in evidence suggests that both raw wood and its composite variants respond differently to thermal input depending on microstructural alignment and interfacial bonding conditions.

Thermal processing of tropical hardwoods also intersects with chemical and mechanical behaviour, as observed in the study on *the effect of alkali pretreatment on mechanical and morphological properties of tropical wood polymer composites* (Saiful Islam et al., 2012). The pretreatment process resulted in changes to fiber crystallinity and surface structure, which in turn impacted thermal conductivity and heat absorption profiles. When considered alongside the findings from Islam et al., (2012) and Flity et al., (2024), it becomes apparent that pretreatment and composite formulation are key parameters influencing thermal performance. The reduction in heat capacity observed in some treated materials implies a higher sensitivity to thermal loading, which is relevant in processes like laser engraving where excessive heat accumulation can lead to undesirable burning depth or charring.

Collectively, these studies demonstrate that the heat transfer characteristics of tropical hardwoods and their composites are influenced by both natural anisotropy and chemical or thermal modifications. The relationship between fiber orientation, composite composition, and pretreatment effects presents important considerations for laser-material interactions. Accurate prediction of burning depth and engraving precision requires a comprehensive understanding of these thermal properties, especially when working with species that have distinct grain structures or have undergone pre-processing. The data reinforce the significance of thermal modelling in guiding parameter optimization for laser applications involving dense wood substrates.

Discussion and Conclusion

The collective findings from studies under the theme of Surface Modification and Material Enhancement underscore the critical role of targeted physical and chemical treatments in improving the performance and resilience of tropical hardwoods, particularly under environmental stress. Treatments such as thermal modification, oil heat treatment, and corona discharge were shown to enhance key surface properties including dimensional stability, moisture resistance, bonding strength, and biological durability. These enhancements not only improved the immediate structural integrity of the wood but also contributed to its long-term resistance against degradation from weathering and microbial attack. The observed improvements in surface energy and fiber morphology suggest that such modifications can also influence how tropical hardwoods respond to external thermal stimuli insights that are directly applicable to laser-based processing applications. As laser engraving involves controlled thermal exposure, understanding how these surface alterations affect energy absorption, charring threshold, and engraving precision becomes vital. Therefore, it can be concluded that pre-treatment of hardwood surfaces significantly contributes to more predictable and

International Journal of Innovation and Industrial Revolution
EISSN: 2637-0972
IJIREV
Volume 7 Issue 22 (September 2025) PP. 749-763
DOI 10.35631/IJIREV.722042
controllable outcomes in laser engraving, enabling better management of burning depth and dimensional accuracy while enhancing overall product longevity.

The reviewed literature on Combustion Behavior and Burning Characteristics highlights the crucial influence of intrinsic wood properties such as density, moisture content, grain orientation, and chemical composition on the ignition resistance, flame propagation, and char formation of tropical hardwoods under thermal exposure. Across the studies, denser species consistently demonstrated slower ignition rates, lower combustion intensities, and greater resistance to thermal degradation, emphasizing the importance of structural composition in fire performance. The empirical relationships established between cumulative heat exposure and char depth further underscore the predictive potential of thermal metrics in modelling burn behaviour. These findings provide a robust foundation for practical applications, particularly in precision-based processes like laser engraving, where depth of burning and thermal damage must be tightly controlled. As a result, the selection of tropical hardwood species for thermal processing should be informed by detailed understanding of their combustion profiles to ensure safe, efficient, and high-quality outcomes.

The studies under the theme of Thermal and Heat Transfer Properties collectively affirm that the thermal response of tropical hardwoods and their composites is deeply influenced by intrinsic anisotropy, fiber alignment, and prior chemical or thermal modifications. Variations in thermal conductivity along different grain orientations, as well as the effects of composite structure and alkali pretreatment, highlight how these factors govern heat absorption and dissipation during thermal exposure. Such properties directly affect the behavior of hardwood materials under laser processing, where localized heating can lead to inconsistent burn depth or surface damage if not properly accounted for. A reduced heat capacity in treated specimens further suggests heightened sensitivity to thermal input, necessitating precision in parameter selection to avoid overburning or dimensional inaccuracy. Thus, a thorough understanding of thermal conduction pathways, material structure, and pre-processing effects is essential for achieving controlled laser engraving outcomes. These insights reinforce the importance of integrating thermal property evaluation into the planning and optimization of laser-based interventions on hardwood substrates.

In summary, the integration of findings across the three thematic domains Surface Modification and Material Enhancement, Combustion Behavior and Burning Characteristics, and Thermal and Heat Transfer Properties provides a comprehensive understanding of how tropical hardwoods respond to thermal-based interventions such as laser engraving. Surface treatments significantly enhance durability and dimensional control, while combustion studies reveal the critical influence of wood density and structure on ignition and charring behaviour. Meanwhile, thermal property investigations underscore the need to account for anisotropic heat flow and the thermal sensitivity of pretreated materials. Collectively, these insights highlight that the precision and effectiveness of laser engraving on tropical hardwoods are highly dependent on the interplay between material composition, surface condition, and heat transfer characteristics. Therefore, successful parameter optimization in laser-based applications must be guided by a multidisciplinary consideration of material science, thermal behaviour, and combustion dynamics to ensure consistent depth control, minimal surface damage, and long-term performance reliability.

Volume 7 Issue 22 (September 2025) PP. 749-763
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Conflicts of Interest
The authors affirm that this study was conducted without any conflicts of interest.

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