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A COMPREHENSIVE STRUCTURED REVIEW OF ENGRAVING TECHNIQUES FOR CONVENTIONAL AND ADVANCED LASER PROCESSING

Anuar Muhammad[1*], Mohd Shahir Kasim[2], Widad Ma3, Ariffatri Mohammad[4]

[1] Faculty of Innovative Design and Technology, Universiti Sultan Zainal Abidin, Malaysia
Email: anuarmuhammad99@gmail.com
[2] Faculty of Innovative Design and Technology, Universiti Sultan Zainal Abidin, Malaysia
Email: shahirkasim@unisza.edu.my
[3] Academy of Language Study, Universiti Teknologi Mara, Dungun Campus, Malaysia
Email: wiema84@gmail.com
[4] Faculty of Business and Management, Universiti Teknologi Mara, Dungun Campus, Malaysia
Email: ariffatriphd@gmail.com

[*] Corresponding Author

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Abstract:

Recent advancements in manufacturing have positioned engraving technologies as critical enablers for precision machining, functional device fabrication, and sustainable production across engineering sectors. However, fragmented research and diverse processing approaches have limited a comprehensive understanding of how conventional and laser-based engraving techniques compare in terms of performance, scalability, and material adaptability. This systematic literature review aims to consolidate current evidence on engraving technologies and assess the evolution of laser-driven innovations by examining studies published between 2021 and 2025. The review followed the PRISMA framework, utilizing Scopus and IEEE databases and applying the search keyword "Engraving Conventional and Advanced" to identify relevant literature. A total of 569 initial records were retrieved, screened based on English-language journal articles, and assessed for eligibility, resulting in 29 primary studies included for synthesis. The selected studies were mapped and thematically analyzed into three core domains: (1) Functional Material Engineering Through Laser Modification, (2) Laser Processing, Optimization & Material Interaction Performance, and (3) Hybrid Fabrication, Low-Cost Manufacturing & Design Technologies. Findings demonstrate that laser-induced modification enables superior functional performance in advanced devices including sensing components, biomedical structures, and photothermal systems. Furthermore, optimization of laser parameters significantly improves machining accuracy, surface characteristics, and structural reliability compared with conventional techniques. Meanwhile, hybrid engraving platforms strengthen sustainable digital manufacturing by supporting cost-efficient prototyping, subsurface structuring, and scalable design solutions. Overall, this review emphasizes the growing dominance of advanced laser engraving in supporting high-value engineering applications and highlights opportunities for future work in comparative processing performance, intelligent optimization models, and industrial-scale adoption of engraving innovations.

Keywords:

Laser Engraving, Conventional Engraving, Advanced Laser Processing, Material Interaction, Hybrid Manufacturing

Introduction

Engraving, as a subtractive manufacturing process, has played a pivotal role in both industrial and artistic domains, evolving from manual and mechanical methods to sophisticated laser-based techniques. The advent of laser processing in the mid-20th century marked a transformative shift, enabling unprecedented precision, repeatability, and versatility in material modification. Conventional laser engraving, primarily utilizing CO_2 and nanosecond-pulsed lasers, established itself as a mainstay in manufacturing, electronics, packaging, and security applications due to its ability to ablate a wide range of materials with high speed and accuracy. However, the increasing demand for finer features, minimal thermal damage, and adaptability to complex geometries has driven the development of advanced laser processing methods, including fiber, MOPA, picosecond, and femtosecond lasers, as well as the integration of robotics and real-time sensor feedback systems. These advancements have not only expanded the scope of engraving applications but also redefined the benchmarks for quality, efficiency, and customization in modern manufacturing and design (Crater, 1987; Tariq et al., 2021; S. Q. Zhang et al., 2014).

The theoretical underpinnings of laser engraving are rooted in the interaction between focused laser energy and material surfaces, where parameters such as power, pulse duration, repetition rate, and scanning speed dictate the nature and extent of material removal. Conventional laser engraving operates on the principle of thermal ablation, where localized heating leads to vaporization or melting of the substrate, producing engraved features with characteristic surface morphologies. While effective for metals, ceramics, polymers, and composites, these methods are often constrained by heat-affected zones, re-deposition, and limitations in feature resolution. Advanced laser systems, particularly those employing ultrafast (picosecond and femtosecond) pulses, mitigate these drawbacks by confining energy deposition to extremely short timescales, thereby minimizing collateral thermal effects and enabling high-precision microstructuring. The introduction of MOPA fiber lasers and combined pulse laser (CPL) technologies further enhances process flexibility, allowing dynamic control over pulse shaping, energy delivery, and material response, which is critical for applications demanding both high throughput and surface integrity (H. Liu et al., 2024; Nikolidakis et al., 2023; Pallares-Aldeiturriaga & Sedao, 2021; D. Zhang et al., 2022).

Volume 7 Issue 23 (December 2025) PP. 294-310
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Literature Review

A significant body of literature underscores the importance of parameter optimization and material-specific process tailoring in achieving desired engraving outcomes. For instance, metals such as steel and aluminium require careful adjustment of laser power, scanning speed, and pulse overlap to balance engraving depth, surface roughness, and thermal effects, while ceramics and composites present additional challenges due to their heterogeneity and varying thermal conductivities. Studies have demonstrated that advanced lasers, when combined with real-time sensor integration such as acoustic emission, infrared imaging, and structured light 3D scanning enable adaptive control of the engraving process, particularly on complex or curved surfaces. Robotic systems equipped with force, torque, and position feedback can dynamically adjust laser trajectories, ensuring consistent power density and feature quality even on non-planar substrates. This convergence of digital design, robotics, and sensor fusion is rapidly transforming laser engraving from a static, parameter-driven process to an intelligent, adaptive manufacturing solution (Alvarez et al., 2025; Cai et al., 2020; Friedel & Wagner, 2012; Roozbahani et al., 2022).

Technological advancements in laser engraving are also characterized by the emergence of hybrid and multimodal processing strategies. Combined pulse laser (CPL) technology, which synchronizes millisecond, nanosecond, and even femtosecond pulses, has been shown to optimize laser-matter interactions, enhance material removal rates, and minimize defects such as micro-cracks and porosity. This approach is particularly advantageous for hard-to-machine materials and high-depth engraving, where single-mode lasers may fall short in efficiency or quality. Moreover, the integration of simulation tools and adaptive control algorithms is increasingly prevalent, enabling predictive modeling of engraving outcomes and reducing reliance on empirical trial-and-error. Such methodological innovations are essential for expanding the applicability of laser engraving to novel materials, including advanced composites and hybrid structures, and for meeting the stringent requirements of next-generation manufacturing (Karbasi, 2008; H. Liu et al., 2024; Rao et al., 2010).

Despite these advances, several research gaps and challenges persist. The literature highlights a need for systematic studies on the effects of laser parameters on less common and composite materials, particularly in the context of high-depth and multimaterial engraving. Real-time monitoring systems, while promising, require further development to robustly integrate multi-sensory data and adaptive control across diverse industrial environments. Additionally, the environmental and economic implications of transitioning from conventional to advanced laser engraving such as energy consumption, process sustainability, and cost-effectiveness warrant comprehensive evaluation. Future research directions are likely to focus on the realization of fully intelligent, digital twin-enabled engraving ecosystems, where simulation, sensor feedback, and robotics converge to deliver real-time process optimization, predictive maintenance, and unprecedented manufacturing flexibility. In summary, the evolution from conventional to advanced laser engraving techniques reflects a broader trend towards precision engineering, material-specific customization, and intelligent process control, positioning laser engraving as a cornerstone of modern and future manufacturing landscapes (James, 2008; Y. Liu et al., 2025; Pallares-Aldeiturriaga & Sedao, 2021; Viviers, 2024; Yang et al., 2024).

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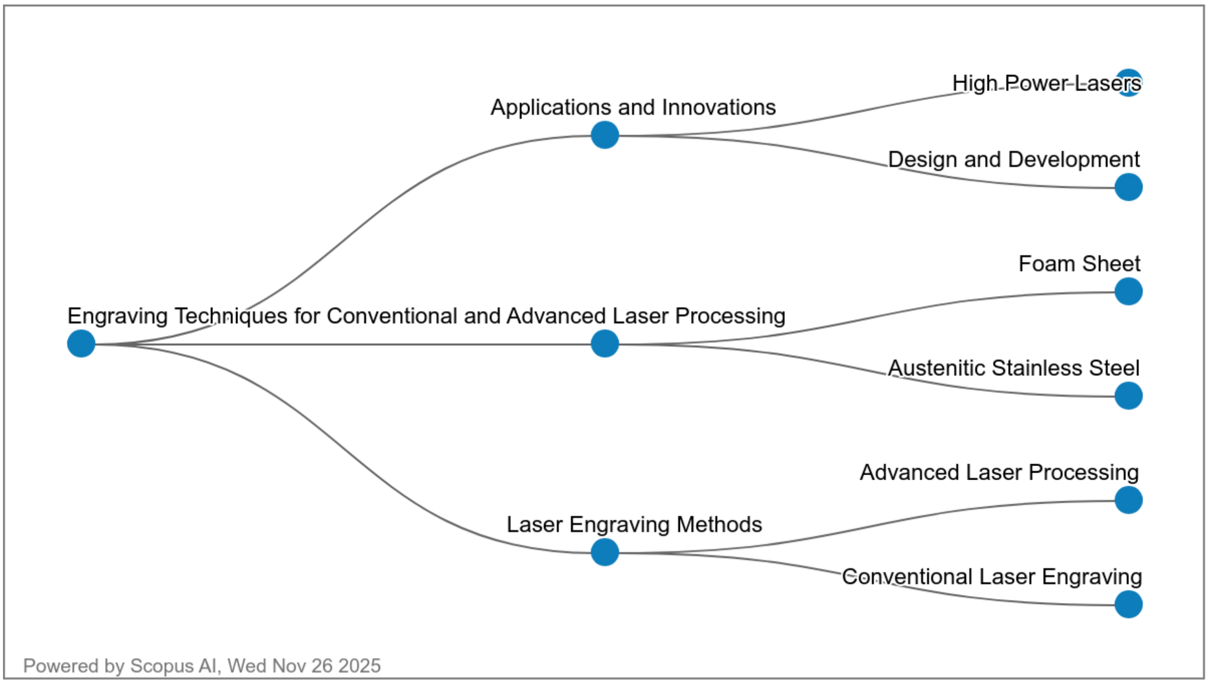

Figure 1: **Research Landscape and Emerging Focus Areas in Engineering Engraving Technologies**

Figure 1 illustrates the core structure of the literature related to engraving techniques for conventional and advanced laser processing, highlighting three dominant clusters: applications and innovations, material-based studies, and methodological development. The applications and innovations cluster emphasizes the growing relevance of high-power lasers and continuous design and development**,** showcasing advancements that improve engraving precision and industrial adoption. Material-focused research, including foam sheets and austenitic stainless steel**,** indicates that material behavior under laser exposure remains a critical determinant of engraving performance and surface integrity. The methodological cluster differentiates between conventional laser engraving and advanced laser processing**,** reflecting the shift from traditional mechanical or lower-power techniques toward optimized laser-based systems that offer superior speed, accuracy, and reduced thermal damage. Collectively, the concept map reveals that optimization strategies, material-specific studies, and technological enhancements are interdependent themes driving current research. Therefore, future investigations should further strengthen comparative performance evaluations while integrating intelligent optimization models such as machine learning to support predictive control and enhance engraving quality across diverse engineering materials.

Material and Methods

Identification

In the Identification stage of this systematic review, comprehensive searches were performed across two highly reputable scientific databases, namely Scopus and IEEE Xplore, to ensure broad and reliable coverage of engineering-related literature concerning conventional and advanced engraving technologies (as shown in Table 1). The selection of these databases is justified by their strong indexing focus in engineering, materials science, industrial manufacturing, and laser processing domains. Using the combined keywords “engraving,” “conventional,” and “advanced,” a total of 351 records were identified from Scopus,

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IJIREV
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representing multidisciplinary studies across mechanical engineering, laser machining, and manufacturing optimization. Meanwhile, 218 records were retrieved from IEEE Xplore, reflecting a strong emphasis on emerging technologies, including high-power laser systems, precision manufacturing, and advanced control models. This combined initial yield of 569 publications reflects a substantial body of knowledge and confirms that the topic has received significant research attention.

The high number of identified records demonstrates both the relevance and growth of laser-based engraving applications in diverse engineering sectors, particularly in optimizing processing parameters and evaluating comparative performance against conventional methods. However, this also indicates potential overlaps, duplicated indexing, and a mix of different material contexts that require further screening. The volume of retrieved studies justifies the need for a structured and rigorous PRISMA workflow to refine relevance, remove redundancy, and ensure only high-quality, methodologically sound records proceed to eligibility and final inclusion. Therefore, the Identification step successfully establishes a strong empirical foundation to support a robust and credible systematic synthesis of engraving techniques for engineering applications.

Table 1: The search string.

Scopus	TITLE-ABS-KEY (Engraving AND (Conventional OR Advanced)) AND (LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2023) 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 (SRCTYPE , "j")) Date of Access: December 2025
IEEE	Engraving AND (Conventional OR Advanced) **Date of Access: December** 2025

Screening

Following the identification phase, all retrieved records underwent a screening process based on predefined eligibility criteria to refine the dataset toward high-quality and relevant sources. Non-English articles, publications prior to 2021, and non-journal sources such as conference proceedings, book chapters, review papers, and in-press manuscripts were excluded to maintain academic rigor and ensure the inclusion of only recent, peer-reviewed contributions within the engineering domain (Table 2). As a result, **435 records** were removed, reflecting substantial elimination of studies outside the intended scope or quality threshold. This procedure retained **134 records** consisting of **75 Scopus** and **59 IEEE** indexed journal articles that met the language, timeline, and publication type requirements. Subsequently, a duplication check was conducted, and **one duplicate entry** was identified and removed. The application of these strict screening criteria ensures that the remaining dataset reflects contemporary and validated insights into engraving techniques, thus strengthening the credibility and reliability of the systematic review findings.

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 7 Issue 23 (December 2025) PP. 294-310
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Table 2: The Selection Criterion is Searching

Criterion	Inclusion	Exclusion
Language	English	Non-English
Time line	2021 – 2025	< 2021
Literature type	Journal (Article)	Conference, Book, Review
Publication Stage	Final	In Press
Subject	Engineering and Material science	Besides Engineering and Material science

Eligibility
During the eligibility phase, full-text access was obtained for 43 articles that successfully passed the prior screening stage. These studies were then assessed in detail for alignment with the review's defined scope, specifically targeting engineering engraving techniques that compare conventional and advanced laser processing performance. This evaluation focused on the sufficiency of methodological reporting, relevance to optimization strategies, and applicability to engraving outcomes on engineering materials. Each article's title, abstract, and methodological sections were examined to ensure clear connection to the review objectives, while also confirming data completeness for qualitative synthesis.

A total of 14 articles were subsequently excluded due to several critical reasons: (i) studies operating outside the intended engineering domain, (ii) content with insufficient relevance where titles lacked specificity and abstracts did not address engraving optimization or performance comparison, and (iii) records without full-text accessibility, preventing thorough evaluation. This left 29 articles that demonstrated strong methodological relevance and direct alignment with the research objectives. These selected studies formed the final dataset used for qualitative analysis and synthesis, ensuring that the conclusions of this systematic review are based on credible, focused, and high-quality empirical evidence related to conventional and laser engraving technologies.

Data Abstraction and Analysis
An integrative analysis approach was employed in this study to systematically examine and synthesise diverse quantitative research designs. The primary objective of this analytical process was to identify key themes and subthemes that align with the focus of this review. The development of thematic structure began with a comprehensive data extraction stage. As illustrated in Figure 2, the authors rigorously reviewed a total of 29 selected publications, coding statements and information directly associated with the topic of engraving techniques in both conventional and advanced laser processing. This included a critical evaluation of research methodologies, experimental parameters, and outcome quality reported in prior studies.

To ensure accuracy and intellectual consensus throughout the thematic development, multiple authors collaboratively engaged in cross-checking and discussion at each stage of interpretation. A research log was consistently maintained to document analytical insights, concerns, and reflections during the coding and interpretation process. In cases of disagreement or ambiguity, the authors engaged in deliberation to reach a shared resolution, ensuring logical consistency and thematic reliability. Once the themes were finalized, refinement was carried out to strengthen coherence and contextual relevance to the research aims. Based on this rigorous synthesis process, the following three research questions were formulated:

1. How do laser engraving techniques influence the functional performance and material properties (e.g., conductivity, optical behaviour, and biocompatibility) across different engineering materials?
2. What are the key laser processing parameters and modelling strategies that determine engraving precision, structural integrity, and overall machining performance compared to conventional methods?
3. How do hybrid digital manufacturing technologies, including laser engraving, contribute to improved cost-efficiency, design flexibility, and sustainable production in advanced and conventional fabrication systems?

Volume 7 Issue 23 (December 2025) PP. 294-310
DOI 10.35631/IJIREV.723020

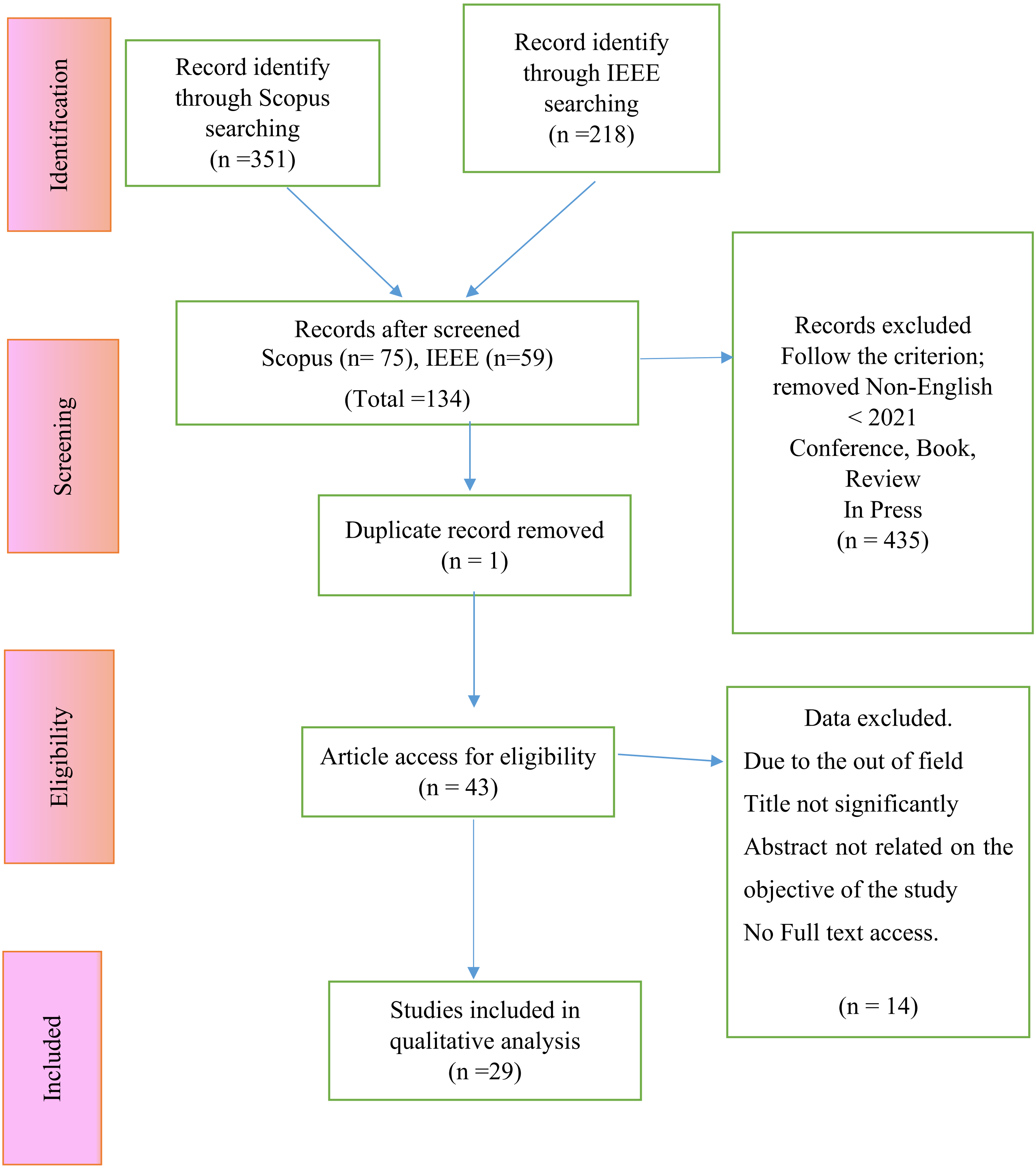

Figure 2. Flow Diagram Of The Proposed Searching Study (Page Et Al., 2021)

Volume 7 Issue 23 (December 2025) PP. 294-310
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Result and Discussion

Functional Material Engineering Through Laser Modification

Laser-based modification of materials has demonstrated significant improvements in functional performance across energy, environmental, and electronic applications. For example, the integration of laser-induced graphene (LIG) onto porous cellulose structures has been shown to produce efficient solar steam evaporators capable of high evaporation rates with practical seawater desalination potential, demonstrating the role of laser engraving in enhancing photothermal conversion for clean water generation (Z. Huang et al., 2025). Comparable enhancements in hydrophobicity and high electrical conductivity have been observed in laser-derived graphene for musculoskeletal tissue scaffolds, illustrating its role in supporting cell proliferation and myogenic differentiation for muscle regeneration applications (Ordoño et al., 2025). Similar strategies utilizing polybenzoxazine precursors have yielded LIG with high graphitization and stability suitable for microsupercapacitors, reinforcing laser engraving as a method for improving electrochemical performance in compact energy systems (Luengrojanakul et al., 2024). Together, these studies emphasize that functional augmentation through laser-induced structural transformation has become an important direction for sustainability, biomedical engineering, and wearable energy storage.

Advanced engraving techniques have also been adopted to improve multifunctional sensing systems. High-conductivity graphene films developed via laser engraving show strong capabilities in detecting both glucose and dopamine with high precision, presenting solutions for point-of-care diagnostics and flexible electronic devices (Ji et al., 2023). Self-sensing shape memory polymer composites have similarly been developed by transferring laser-induced graphene to PLA substrates, enabling real-time monitoring of deformation under electrical or photothermal stimuli (Gholami et al., 2024). Meanwhile, engineered nanocomposites fabricated on SiO_2 glass using femtosecond laser structuring have been used to achieve efficient electromagnetic interference (EMI) shielding while retaining transparency, strengthening their potential for aerospace and telecommunications infrastructures that require both robustness and visibility (Khalil et al., 2025). Collectively, these research efforts reflect a clear trajectory toward multifunctional devices driven by laser-assisted patterning and conductivity enhancement.

Laser engraving has also broadened possibilities in optical and structural functionalization. Saddle-shaped phosphor-in-glass structures engraved with lasers have been shown to improve illumination and color stability in large-view LEDs, outperforming conventional phosphor configurations in luminous efficiency and heat durability (H.-W. Huang et al., 2024). In design-oriented materials, laser-enabled modification has facilitated the creation of ultra-light and highly flexible graphene meta-aerogels, merging sculptural aesthetics with unprecedented elastic performance (M. Zhang & Yuan, 2022). Even traditional materials, such as wood, have benefited from modern engraving methodologies, where laser or CNC-based motif transposition enables improved surface detailing and preservation of cultural ornamentation in furniture applications (Lungu et al., 2022). These studies collectively validate laser engraving as a transformative fabrication strategy capable of enhancing optical behavior, structural adaptability, and aesthetic value.

Volume 7 Issue 23 (December 2025) PP. 294-310
DOI 10.35631/IJIREV.723020

Overall, research progress in functional material engineering through laser modification demonstrates strong convergence in efficiency enhancement, precision microstructuring, and multi-performance integration. Across the reviewed studies, laser engraving acts not only as a subtractive tool but also as a mechanism to engineer performance-driven surfaces, particularly in desalination systems, biosensing, smart materials, transparent EMI shielding, advanced LED systems, and heritage-inspired design. The consistent evidence suggests that functional improvement relies on the synergy between laser processing parameters, material chemistry, and microstructural evolution, supporting future directions toward scalable manufacturing of high-value functional components.

Laser Processing, Optimization and Material Interaction Performance

Research focusing on laser material interaction consistently highlights how laser input parameters govern machining efficiency, dimensional accuracy, and surface morphology. Findings from investigations on hybrid glass-fiber reinforced polymers show that greater laser power and higher scanning speeds enhance material removal rate, yet they also contribute to rougher surfaces and microstructural defects such as microcracks and debris deposition (Mehra et al., 2025). Similar sensitivity to parameter variation is emphasized in the machining of titanium alloys, where the roughness distribution, isotropy of texture, and functional lubrication behaviour shift notably based on the power–speed–frequency combination (Nikolidakis et al., 2025). Parameter-dependent outcomes also appear in the fabrication of micro Fresnel lens moulds, where laser power is identified as the most influential contributor to roundness deviation, followed by scan speed and cycle number, confirming that precision in optical components is highly reliant on optimized parameter ranges (Datta & Goswami, 2024). These studies collectively demonstrate that effective laser machining requires careful balancing of energy density and movement trajectory to achieve acceptable surface profiles and structural consistency.

The importance of real-time subsurface assessment and high-resolution defect characterization has also been emphasized in laser engraving research. High-speed X-ray phase imaging enables observation of internal ablation behaviour in polymers, capturing bubble formation and delayed thermal effects during engraving, which offers deeper insights beyond surface-only evaluation methods (Ueda et al., 2023). Related investigations into microstructured glass light guide plates demonstrate how concave microfeatures produced by pico-laser pulses maintain uniform luminance when used within display backlighting systems, indicating that deliberate microgeometry formation plays a critical role in optical uniformity and performance (Teng et al., 2022). Comparable precision-engineering concerns arise in microwave dielectric ceramic filters, where laser trimming reduces dimensional error and improves line-width accuracy relative to screen-printing approaches, resulting in better alignment to target frequency bands and lower insertion losses (Lin et al., 2021). Together, these studies highlight that deeper visualization, dimensional trimming, and microstructure calibration form essential mechanisms for controlling performance in laser-based manufacturing.

Optimization of functional electrode and membrane systems using laser interaction further extends the relevance of the processing–performance relationship. The development of ultrathin inorganic membranes shaped through femtosecond laser engraving confirms that well-defined pore geometries and hydrophobic modifications contribute to high stability extraction processes in microseparation devices, supporting wider operating ranges than organic membrane alternatives (Nie et al., 2022). Enhancements achieved in laser-processed

Volume 7 Issue 23 (December 2025) PP. 294-310
DOI 10.35631/IJIREV.723020

electrocatalytic structures also reinforce this trend. Oxygen-vacancy-engineered NiO nanosheets prepared through plasma engraving facilitate improved electrochemical activity in Li-CO_2 batteries, with modified electronic states contributing to better adsorption behaviour and enhanced cycling performance (Wang et al., 2021). In microheater production, laser-engraved titanium nitride thin films exhibit stable heating characteristics and favourable resistivity profiles, offering a more scalable and economical alternative to conventional lithographic processing (M.a et al., 2022). These findings indicate that advanced laser processing not only affects geometric accuracy but also reshapes electronic, catalytic, and thermomechanical properties, enabling higher operational efficiency across functional component applications.

Hybrid Fabrication, Low-Cost Manufacturing and Design Technologies

Recent developments in hybrid and digitally integrated fabrication techniques show strong potential for improving microfluidic manufacturing, particularly where reduced cost, accessibility, and flexibility are required. The introduction of low-cost laser engraving using heat-shrink plastics allows the production of multilevel semicircular microchannels capable of supporting controlled droplet generation, making this approach a feasible alternative to traditional cleanroom-based lithography (Yoo et al., 2025). Similar emphasis on process accessibility is demonstrated through 3-in-1 desktop fabrication systems, where integrated 3D printing, CNC milling, and laser engraving enable rapid prototyping with adequate microfluidic performance for laboratory or educational contexts (Thaweeskulchai & Schulte, 2021). Transitions toward sustainable digital manufacturing also appear in industrial settings, with additive-manufacturing-driven redesigns reducing CO_2 emissions and raw material consumption while maintaining similar production costs compared to conventional machining pathways (Top et al., 2023). These findings indicate that cost reduction and environmental efficiency are key outcomes of combining engraving technologies with adaptable fabrication platforms.

Advances in laser structuring have also enabled the formation of engineered subsurface and nanoscale features that support high-performance optical and diffractive devices. The application of Bessel beams to embed diffractive elements deep within optical glasses demonstrates that chemical-free processes can generate efficient large-volume microstructures suitable for optical holography (Fantova et al., 2024). Comparable subsurface precision is shown in the creation of periodic nanohole arrays in fused silica, where adjustable beam shaping allowed depths up to 20 µm while preventing high-density pattern interference during fabrication (X. Liu et al., 2023). Moreover, improvements in light guiding behaviour through pico-laser-engraved concave structures on glass plates support uniform luminance in display backlight systems, confirming that controlled microstructuring directly enhances optical uniformity (Teng et al., 2022). Collectively, these works underline that accurate and versatile engraving-based nanofabrication offers viable pathways to replace more complex photolithographic processes in optical component manufacturing.

In conventional machining, new toolpath strategies and optimized design methods continue to address performance and manufacturability limitations in engraved structures. A newly proposed trochoidal milling path has shown the ability to maintain cutting force consistency while improving surface finish and reducing tool wear, offering advantages in mould and die fabrication where engraving geometry is complex (Kiyak et al., 2023). The integration of sequential dynamic modelling and enhanced optimization in artillery-launch engraving

International Journal of Innovation and Industrial Revolution
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IJIREV
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processes further illustrates the relevance of advanced computation, where improved convergence stability enhances muzzle performance and operational precision (Xie et al., 2023). Enhanced engravability is also demonstrated in thin-shell design applications, where parametric patterning avoids remeshing requirements and maintains structural stiffness while reducing material use (Hu et al., 2023). These studies confirm that algorithm-enabled toolpath and structural optimization are increasingly important to simultaneously achieve precise engraving performance and efficient resource utilization.

Conclusion

This systematic literature review was conducted to consolidate fragmented knowledge relating to engraving techniques across both conventional and advanced laser processing domains. The objective was to examine how recent studies, published from 2021 to 2025, contribute to the evolution of engraving performance, material interaction behavior, and industrial feasibility. The review applied the PRISMA methodology and relied on two leading databases Scopus and IEEE to ensure the credibility, engineering relevance, and scientific rigor of the selected works. From an initial dataset of 569 records, only 29 primary studies met the inclusion criteria and were eligible for thematic synthesis. Three research questions guided the review: (i) the extent to which laser engraving influences functional material performance, (ii) the determining role of laser processing parameters in shaping machining precision and structural properties, and (iii) the contributions of hybrid digital manufacturing to cost-efficiency and sustainability. Findings were then structured into three dominant themes: Functional Material Engineering Through Laser Modification, Laser Processing, Optimization & Material Interaction Performance, and Hybrid Fabrication, Low-Cost Manufacturing & Design Technologies. The synthesis highlights a strong technological progression in the field, particularly the transition from traditional subtractive machining toward intelligent, digitally enhanced engraving systems.

The findings demonstrate that advanced laser systems, including femtosecond, picosecond, and MOPA fiber lasers, have transformed engraving into a versatile platform for both structural and functional engineering. Laser-induced graphene and engineered nanocomposites are enabling high-value applications in energy harvesting, biomedical scaffolds, lightweight shielding, photonics, and flexible electronics areas where conventional engraving techniques cannot provide comparable precision or functional enhancements. Meanwhile, parameter optimization and real-time monitoring have emerged as critical factors governing success in engraving outcomes. Surface roughness, dimensional accuracy, morphology control, and defect suppression depend heavily on the power speed pulse interaction, demonstrating the need for intelligent parameter models and multi-physics characterization during processing. Additionally, emerging subsurface and nanoengraving strategies offer superior pattern definition without conventional photolithography, supporting new product innovations in optical and dielectric devices. The third thematic strand shows that hybrid digital manufacturing methods combining engraving with additive, CNC, and low-cost fabrication systems advance process accessibility and sustainability while promoting design freedom and reduced waste. The review not only categorizes engraving research based on functional, process-engineering, and cost-performance priorities but also develops a clearer conceptual understanding of how material behavior and advanced laser control strategies converge to drive technological enhancements in this field. Overall, the synthesis establishes that laser engraving has shifted from a basic subtractive technique to a core enabler for new-generation smart manufacturing systems.

This systematic review contributes to the body of knowledge by establishing a novel thematic structure that can serve as a reference model for future classification of engraving-related studies. The review clarifies the capabilities and limitations of both conventional and advanced approaches, helping to guide industrial decision-making where trade-offs between quality, scalability, and operational costs must be considered. In practice, the reported improvements in surface finish, functional performance, and device integration support wider industrial adoption of laser engraving across precision sectors including aerospace, optics, microelectronics, sustainable energy, and healthcare device prototyping. However, several limitations must be acknowledged. The reliance on only two databases and English-language filters excludes studies from other domains that may contribute alternative insights. The timeframe restriction to 2021–2025 offers a contemporary focus but may overlook foundational progress achieved in earlier years. More importantly, few studies provide direct comparative evaluation between conventional and advanced techniques under standardized operational benchmarks, indicating that further experimental work is necessary to bridge theoretical claims with practical industrial deployment. Future research should expand towards machine learning based predictive models for parameter optimization, multiphysics simulation for laser-matter interactions, and techno-economic assessment of industrial scalability. It is also recommended that researchers examine environmental sustainability indicators such as energy use, emission factors, and material circularity to support greener manufacturing transitions. In conclusion, this review emphasizes the value of systematic synthesis in maintaining coherence within rapidly evolving fields such as laser engraving. By integrating cross-disciplinary findings and analyzing emerging research directions, systematic reviews contribute significantly to evidence-based innovation, ensuring that advancements in engraving technologies continue to align with industrial demands, material challenges, and global sustainability goals.

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Conflicts of Interest
The authors declare that no competing interests exist in connection with the content of this article.

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