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# INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

**Volume:** 2026 **Issue:** Conference **Month of publication:** May 2026

**DOI:** https://doi.org/10.22214/ijraset.2026.83179

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International Journal for Research in Applied Science & Engineering Technology (IJRASET)
*ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538*
*Volume 14 Issue V May 2026- Available at www.ijraset.com*
*National Conference on Integrated Approaches to Sustainable Innovation 2026 (IASI 2026)*

# Eco-Efficient Laser Beam Machining Integrating Green Technology with Advanced Manufacturing Systems

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***Abstract:*** ***It should be noted that Laser Beam Machining (LBM) has become a revolutionary technology that allows for obtaining high precision, low tool wear and versatility in working with different materials. Against the backdrop of the growing environmental awareness and transition of industry to sustainable manufacturing, LBM attracts considerable interest as one of the most important technologies that can ensure the development of green manufacturing. This review is dedicated to studying the problem of ecoefficient laser beam machining in the framework of advanced manufacturing and green technologies. In particular, the work will describe the fundamentals of LBM as well as analyze some issues related to the interaction between laser beam and material, heat transfer and process parameters. It is necessary to pay special attention to new types of lasers – fiber, ultrafast and diode-pumped solid-state lasers due to their increased energy efficiency, less negative impact and sustainability; the use of LBM in intelligent manufacturing systems, such as digital monitoring, automation, and optimization, is explored as an approach to create sustainable industrial ecosystems. Moreover, the paper deals with the evaluation of the impact of the process on the life cycle, energy consumption, and carbon footprint. New inventions in LBM regarding sustainability, including the use of hybrid machining, adaptive control, and use of renewable energy, are discussed. Future research directions in the field, which would involve efforts to improve process efficiency and minimize environmental impact, are proposed in the concluding section of the paper.***

***Keywords: Laser Beam Machining, Sustainable Manufacturing, Green Technology, Energy Efficiency, Eco-Friendly Processing.***

## I. INTRODUCTION

It is notable to mention that Laser Beam Machining (LBM) has proved to be a revolutionary technology in the field of machining processes. Contrary to other manufacturing techniques, LBM involves focusing of a laser beam on a workpiece material surface with the aim of causing melting, burning, or vaporization of material through localized heating process [1-4]. This manufacturing process does not necessarily require any form of mechanical contact and, therefore, it is not associated with excessive material wear like other methods [5-6]. The importance of LBM technology can only be recognized in highly precise and micro-scale manufacturing in different fields including aerospace, biomedical engineering, electronics, and automotive production [7-8].

As much as machining processes are vital in manufacturing, it has been discovered that most traditional technologies are not environmentally friendly because of their adverse effects on the environment [9-11]. The major problem associated with these technologies is the large amounts of material wastages generated, the requirement for cutting fluids, and high energy consumption during production. It becomes quite difficult to ensure that these processes will remain sustainable in the future. However, laser beam machining provides an environmentally sustainable manufacturing technology since it can minimize these challenges [12-13].

Moreover, developments in laser technologies, including the emergence of fiber, ultrafast, and diode-pumped solid-state lasers, have greatly increased the energy efficiency and environmental performance of the LBM technology. Modern devices ensure improved beam quality, minimize thermal effects, and reduce expenses, thus, allowing using the LBM technology for more environmentally friendly purposes [14-17]. In addition, the use of LBM technology in combination with digital manufacturing tools, such as automation, monitoring, and artificial intelligence, will enhance its contribution to creating sustainable industrial ecosystems.

While all those features can be considered among the key benefits of the LBM technology in terms of sustainable manufacturing, there are also several challenges that need to be taken into account [18-20]. They include the significant amount of energy used in the process, high initial expenditures, and inability to apply the technology to some materials. Given all those aspects, conducting a comprehensive review on the subject matter becomes critically important.

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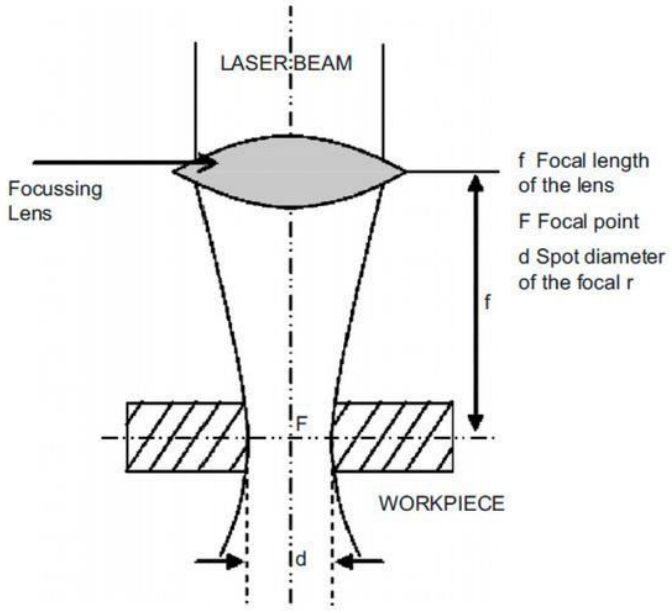



Fig 1. Beam profile schematic for laser beam machining applications. Reproduced with permission from Pramanik et al., *Metals, 13(9), 1536.* (2023). Copyright 2023 Authors, licensed under a Creative Commons Attribution (CC BY) license.

TABLE I
COMPARISON OF CONVENTIONAL MACHINING AND LASER BEAM MACHINING

| Parameter | Conventional Machining | Laser Beam Machining (LBM) |
|---|---|---|
| Tool Contact | Direct contact with tool | Non-contact process |
| Tool Wear | High | Negligible |
| Material Removal | Mechanical cutting | Thermal (melting/vaporization) |
| Precision | Moderate | Very high |
| Material Compatibility | Limited (hard materials difficult) | Wide range (metals, ceramics, polymers) |
| Use of Cutting Fluids | Required | Minimal or not required |
| Waste Generation | High | Low |
| Environmental Impact | Higher | Lower |
| Energy Efficiency | Moderate | High (with advanced lasers) |

## II. OBJECTIVES

One of the main goals of the current paper is going to be assessing the usefulness of LBM in sustainable manufacturing. As industries increasingly pay attention to environment-friendly processes, there is a need for an assessment whether new manufacturing technologies can be classified as sustainable. Thus, this work is aimed at gaining an insight into the potential of LBM technologies from this perspective.

Another important purpose of the paper is to evaluate the principles of LBM technology and their contribution to making ecoefficient machining processes possible. The analysis will be focused on such issues as the nature of laser-material interaction and its effects, thermal properties of processes, and the role played by different process parameters in achieving optimal results in the context of sustainability.

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Fig 2. Green technology is integrated with advanced manufacturing systems in eco-efficient laser beam machining.

It is important to mention that the impacts of innovative lasers, such as fiber lasers, ultrashort pulsed lasers, and diode-pumped solid-state lasers (DPSSLs), should also be considered. Innovations have proved to be more effective in terms of energy efficiency, small heat-affected zones, and process stability, which contributes greatly to waste reduction and lowering of the environmental load [21-23]. The review also intends to explore the possibilities of using LBM alongside with intelligent and digital manufacturing systems. Application of automation technologies, monitoring of the processes, and optimization of the procedures will help to improve the process and reduce consumption. Moreover, the environmental effect of LBM should be assessed by carrying out LCA, analyzing energy consumption, and evaluating the carbon footprint of the process [24-26]. In order to understand which factors affect environmental performance of LBM, we need to identify them.

TABLE 2
TYPES OF LASERS USED IN LBM AND THEIR CHARACTERISTICS

| Laser Type | Key Features | Advantages | Limitations |
|---|---|---|---|
| Fiber Laser | Solid-state, optical fiber medium | High efficiency, low maintenance | High initial cost |
| Ultrafast Laser (Femtosecond) | Extremely short pulse duration | Minimal heat-affected zone, high precision | Expensive, complex system |
| $CO_2$ Laser | गैस-based laser | Good for non-metals, high power | Lower efficiency, bulky system |
| Diode-Pumped Solid-State (DPSS) | Semiconductor-pumped crystal laser | Compact, energy efficient | Limited power compared to fiber |
| Nd:YAG Laser | Solid-state laser | Suitable for metals, stable output | Moderate efficiency |

Finally, it is important to suggest possible future research directions and technological innovations that may further enhance eco-efficiency of LBM.

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## III. METHODOLOGY

In this research work, the use of a systematic and comprehensive review technique will be employed in examining the role of Laser Beam Machining (LBM) in sustainable manufacturing and green technology. This technique includes gathering, evaluating, and synthesizing data from various sources such as research studies, review studies, and technical papers regarding LBM techniques and laser machines as well as their performance in terms of sustainability and environment [27-29].

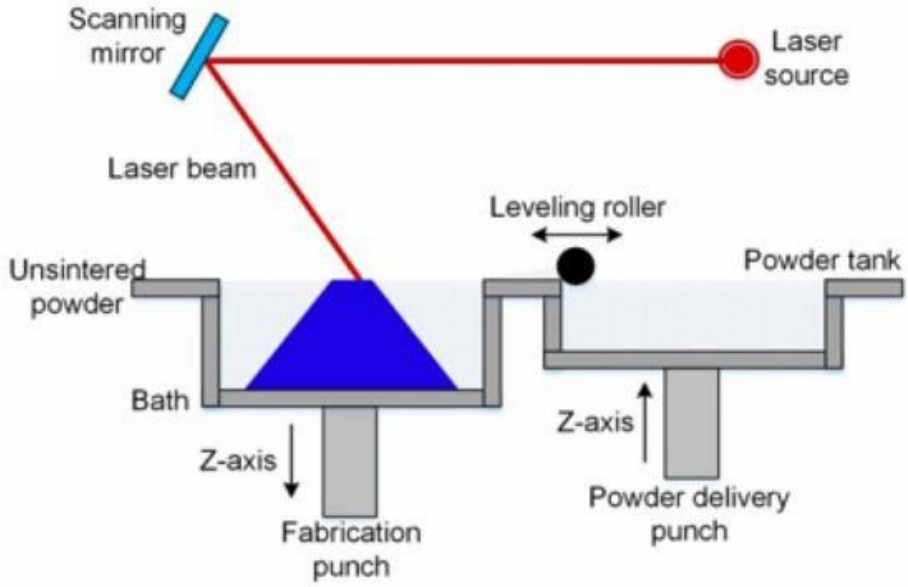



Fig 3. Diagram of SLS from laser sintering to 3D CAD design. Reproduced with permission from Dipta et al., *Journal of Manufacturing and Materials Processing, 9(8), 269.* (2025). Copyright 2025 Authors, licensed under a Creative Commons Attribution (CC BY) license.

The initial stage of this methodology is an examination of basic concepts of LBM techniques. Such concepts include the mechanism of laser-material interaction, the nature of energy absorption and heat transfer during machining operation [30-32]. All these concepts are essential for comprehending the effects of machining variables on machine performance.

TABLE 3
SUSTAINABILITY ASSESSMENT OF LBM

| Sustainability Aspect | LBM Performance | Impact on Environment |
|---|---|---|
| Energy Consumption | Moderate to High | Can be reduced with efficient lasers |
| Material Waste | Very Low | Reduces raw material usage |
| Emissions | Low | Lower greenhouse gas emissions |
| Cutting Fluids Usage | Minimal | Reduces chemical pollution |
| Carbon Footprint | Lower than conventional methods | Supports green manufacturing |
| Noise Pollution | Low | Safer working environment |
| Recycling Potential | High (less contamination) | Promotes circular economy |

Also, the method comprises an evaluation of new technologies in laser machines like the fiber laser, ultrafast laser, and diode-pumped solid state laser [32-34]. These technologies will be assessed on the basis of their sustainability concerning energy efficiency and accuracy. Comparative assessment will be done to identify whether or not the technology is suitable for sustainable production applications.

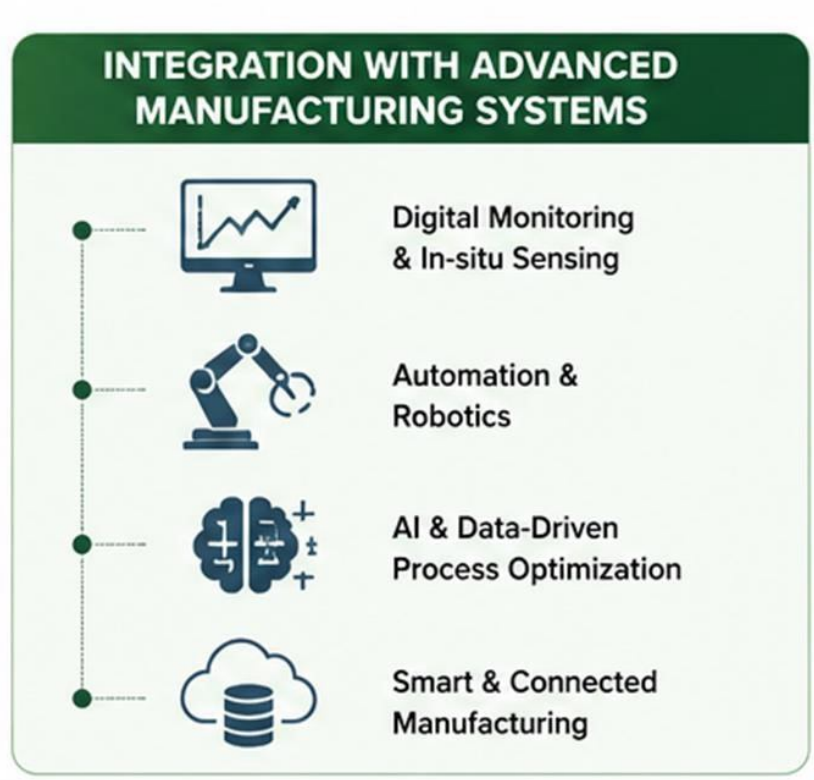



Fig 4. LBM integration with advanced manufacturing systems.

In addition to this, LBM incorporation into intelligent manufacturing systems will also be covered. This includes the evaluation of different approaches and technologies utilized in intelligent manufacturing that include the utilization of feedback mechanisms in digital operations, process automation, and artificial intelligence. All these technologies enable real-time control of the process, greater accuracy, and reduced energy wastage, and therefore, enhance sustainability [35-37].

Another key step of the methodology is that of environmental evaluation. Life cycle assessment technologies are used to evaluate the impact of LBM operations on the environment due to energy usage, emissions, and waste production. Other methods that could be used in environmental assessment include carbon footprint assessment and energy consumption modelling [38-39]. Such approaches will be evaluated to establish the extent of their role in enhancing the sustainability of LBM.

TABLE 4
KEY CHALLENGES AND FUTURE DIRECTIONS IN LBM.

| Category | Current Challenges | Future Directions |
|---|---|---|
| Economic | High initial investment | Cost reduction through mass adoption |
| Technical | Difficulty with reflective materials | Advanced beam control and coatings |
| Energy | High operational energy demand | Integration with renewable energy sources |
| Process Control | Sensitivity to parameter variation | AI-based adaptive control systems |
| Skill Requirement | Need for skilled operators | Automation and user-friendly interfaces |
| Sustainability | Limited LCA data availability | Comprehensive environmental modeling |
| Innovation | Limited hybrid integration | Development of hybrid and multi-process systems |

## IV. CONCLUSIONS

The use of Laser Beam Machining (LBM) in Sustainable Manufacturing highlights the vast capabilities of LBM as an ecoefficient process. The first factor associated with LBM is its ability to considerably minimize wastage. It is because LBM is known for its accuracy and precision in material removal. Thus, unlike in conventional machining techniques, where a significant amount of material is wasted during production, LBM makes it possible to effectively conserve materials by minimizing waste. Another significant feature about LBM is that it is a non-contact method, hence eliminating tool wear and tear. An important thing to be noted from the analysis of the reviewed article is the limited use of cutting fluid in LBM. Cutting fluid has long been used in conventional machining as coolant but poses serious environmental risks, mainly pollution. However, LBM requires minimal use of cutting fluid. In addition, with recent advancements in laser technology, including the application of fiber and ultrafast lasers, energy efficiency has been greatly enhanced through reduced thermal damage.

Incorporation of LBM into the modern concept of smart manufacturing systems provides further possibilities of LBM sustainability. In particular, technologies, including real-time monitoring and artificial intelligence, provide precise control of process parameters, minimizing waste of energy and optimizing productivity. Optimization methods based on big data analysis help improve machining processes continuously to achieve effective resource utilization. On the other hand, there are several drawbacks related to laser beam machining discussed in the research. One of the problems with laser machining is the relatively high price and high-energy consumption required by the technology. Besides, not all materials can be machined by lasers efficiently, specifically reflecting and heat-sensitive ones. Nevertheless, these disadvantages are constantly being improved by researchers. New approaches, including hybrid machining systems, adaptive controls, and utilization of sustainable energy sources, can potentially increase LBM efficiency and expand material capabilities of the technology. This indicates that LBM will continue being one of the central technologies for green manufacturing in the future. The following directions should be addressed to improve LBM in the future.

## V. ACKNOWLEDGMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request. The authors have no conflicts to disclose.

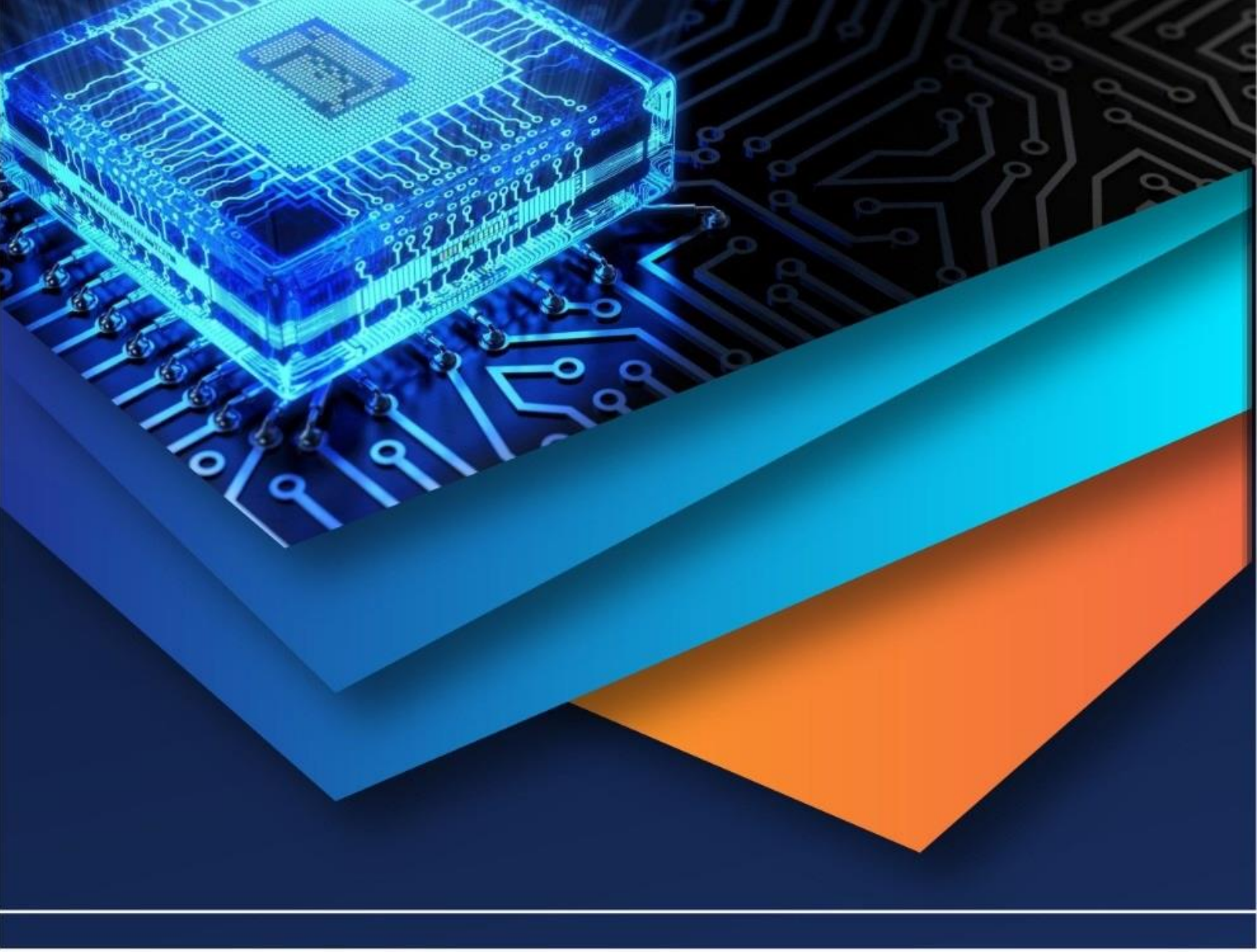
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