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Review Article

Understanding Laser Induced Breakdown Spectroscopy: An Overview

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ABSTRACT

Laser-Induced Breakdown Spectroscopy (LIBS) is a cutting-edge analytical technique that employs high-energy laser pulses to create plasma from a material, enabling the detection of multiple elements through the analysis of emitted light. This review delves into the fundamental principles of LIBS, emphasizing the role of plasma formation and spectral emission in elemental identification. Key components of LIBS instrumentation, including the laser source, focusing optics, and spectrometer, are detailed alongside analytical methodologies that enhance precision and accuracy. The review explores critical factors influencing LIBS performance, such as matrix effects, environmental conditions, and signal processing techniques. LIBS' versatility is showcased through its applications in diverse fields, including material characterization, environmental monitoring, and biomedical analysis. The technique's advantages, such as minimal sample preparation, rapid analysis, and multi-element detection, are discussed alongside its limitations, including matrix effects and sensitivity challenges. Recent advancements, including person-portable devices and machine-learning algorithms for spectral analysis, are highlighted as transformative developments. Emerging trends suggest expanding applications in areas like cultural heritage preservation, industrial automation, and planetary exploration. By synthesizing current knowledge and identifying research gaps, this review aims to deepen understanding, promote innovation, and guide future research in Laser-Induced Breakdown Spectroscopy.

INTRODUCTION

Laser Induced Breakdown Spectroscopy (LIBS) is a cutting-edge analytical technique that has

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revolutionized elemental analysis by providing rapid, real-time results with minimal sample preparation. This method employs high-energy laser pulses to ablate a small amount of material, generating plasma that emits characteristic light used for qualitative and quantitative elemental analysis. LIBS has emerged as a versatile tool across diverse fields, from material science and environmental monitoring to space exploration and biomedical applications.

1.1. Brief History of LIBS Development and Evolution

The concept of using laser-induced plasma for elemental analysis dates back to the 1960s when Brech and Cross introduced the technique [1]. However, its widespread adoption was limited due to the technological constraints of early laser systems. The development of Q-switched lasers in the 1980s significantly improved the precision and efficiency of LIBS, enabling its application in scientific and industrial domains [2]. By the 1990s, advancements in spectrometers and data processing algorithms enhanced LIBS's analytical accuracy, paving the way for portable and field-deployable systems in the 21st century [3].

1.2. Importance of LIBS in Modern Analytical Chemistry

LIBS stands out in modern analytical chemistry for its ability to provide fast, multi-elemental analysis with minimal sample preparation. Unlike traditional methods such as atomic absorption spectroscopy (AAS) or inductively coupled plasma mass spectrometry (ICP-MS), LIBS do not require extensive pre-treatment, making it ideal for real-time and in situ analysis [4]. Furthermore, LIBS's versatility in analysing solids, liquids, and gases expands its applicability across various industries, including metallurgy, environmental monitoring, and biomedical diagnostics.

1.3. Unique Advantages Over Other Analytical Techniques

1. **Speed and Efficiency:** LIBS enables near-instantaneous analysis, significantly reducing the time required compared to techniques like ICP-MS [4].
2. **Portability:** Modern LIBS systems are compact and portable, facilitating field analysis and reducing the dependency on laboratory settings [5].
3. **Non-Destructive or Minimal Destruction:** While minimal ablation occurs during the analysis, the overall damage to the sample is negligible compared to other destructive techniques [6].
4. **Versatility:** LIBS can analyse virtually any material, from metals and polymers to biological tissues and geological samples, without needing different sample preparation protocols [7].
5. **Simultaneous Multi-Element Detection:** Unlike many analytical methods that analyse one element at a time, LIBS provides a full spectrum for multi-elemental analysis [8].

2. Principle of LIBS

Laser Induced Breakdown Spectroscopy (LIBS) operates on the principle of laser-induced plasma formation, followed by the spectral analysis of the emitted light. This process involves the interaction of a high-energy laser with the material, which ablates a small portion of the sample and generates a hot plasma. The spectral emission from this plasma contains information about the elemental composition of the sample, enabling qualitative and quantitative analysis.

2.1. Fundamental Physics Behind Laser-Material Interaction

The LIBS process begins with the interaction of a focused laser pulse with the surface of a sample. When the laser energy exceeds the material's ablation threshold, it causes localized heating, melting, and vaporization of the sample surface. This is followed by ionization of the vaporized material, creating a plasma—a highly ionized,

high-temperature state of matter containing electrons, ions, and neutral atoms [9].

The efficiency of laser-material interaction depends on several factors, including laser wavelength, pulse duration, energy density, and the material's thermal and optical properties. Short laser pulses (nanoseconds or femtoseconds) ensure that the laser energy is deposited before significant heat diffusion occurs, improving ablation precision [10].

2.2. Process of Plasma Generation and Spectral Emission

1. **Plasma Formation:** The laser pulse ablates the sample surface, generating a plume of vaporized material. The high-energy density of the laser pulse causes this plume to ionize, forming a plasma with temperatures often exceeding 10,000 K [11].

2. **Plasma Expansion and Cooling:** The plasma rapidly expands, cools, and emits light due to radiative recombination, electron-ion collisions, and transitions of excited atoms and ions. The emitted light spans a broad spectrum, with sharp peaks corresponding to the characteristic wavelengths of the elements present in the sample [12].

3. **Spectral Analysis:** The emitted light is collected by a spectrometer and analyzed to determine the elemental composition. Each element has a unique spectral fingerprint, allowing for its identification and quantification [13].

2.3. Role of Ablation and Ionization in the LIBS Process

Laser ablation involves the removal of material from the sample surface due to high-energy laser irradiation. This step is critical for LIBS as it provides the material necessary for plasma generation. The ablation depth and volume depend on the laser parameters and the sample's properties, such as hardness and reflectivity [14].

Ionization is the process through which neutral atoms in the ablated material lose electrons, resulting in the formation of plasma. The degree of ionization directly affects the intensity of the spectral emission and, consequently, the sensitivity of the LIBS analysis. A higher degree of ionization leads to stronger emission lines, facilitating more accurate detection of trace elements [15].

3.Instrumentation and Components of LIBS

The successful operation of a Laser Induced Breakdown Spectroscopy (LIBS) system relies on several key components that work in synergy to produce and analyze the plasma generated by the laser-material interaction. Below is a detailed description of the major components of a LIBS system:

3.1. Laser Source

The laser is the core element of a LIBS system, responsible for delivering the high-energy pulse needed to ablate the sample and generate plasma. The most common laser types used in LIBS are:

- **Nd:YAG Lasers**: Neodymium-doped Yttrium Aluminum Garnet (Nd:YAG) lasers are widely used due to their high energy output, short pulse durations (typically nanoseconds), and versatile wavelength options (e.g., 1064 nm, 532 nm) [16]. These lasers are ideal for solid, liquid, and even gaseous sample analysis.

- **Femtosecond Lasers**: These lasers generate pulses on the order of femtoseconds (fs), providing ultra-short durations that minimize thermal effects during ablation. They are especially useful for precise, high-resolution analyses [17].

- **Wavelength and Energy**: The wavelength of the laser is typically chosen based on the material's absorption characteristics. Common wavelengths include 1064 nm, 532 nm, and 355 nm, with energies ranging from

a few mJ to several hundred mJ, depending on the application [18]. The energy requirements are usually governed by the sample's ablation threshold, which determines the amount of laser energy needed for effective plasma formation.

3.2. Optical System

The optical system of a LIBS device focuses and directs the laser beam onto the sample and captures the emitted light from the plasma. Key components include:

- **Lenses**: Convex lenses are used to focus the laser pulse onto the sample's surface. The quality of these lenses directly affects the laser spot size and the energy density delivered to the sample, which in turn influences the efficiency of plasma generation.
- **Mirrors**: Mirrors are employed to direct the laser beam and collect emitted light from the plasma. The use of mirrors with high reflectivity and minimal distortion is essential for maintaining system accuracy and efficiency.
- **Focusing Mechanism**: The focal length and alignment of the optical system ensure that the laser energy is concentrated on a small area of the sample. This enables precise plasma generation with minimal sample damage.

3.3. Spectrometer

A spectrometer is used to collect and analyze the light emitted by the plasma. The spectral lines produced during plasma cooling provide information about the elemental composition of the sample.

- **Types**: LIBS systems typically employ either **grating** or **prism spectrometers**. Grating spectrometers are more common due to their ability to cover a wide wavelength range and provide higher resolution [19].
- **Resolution Considerations**: The resolution of the spectrometer determines the ability to distinguish between closely spaced spectral lines. Higher resolution spectrometers allow for better separation of overlapping peaks, which is especially important when dealing with complex sample matrices or trace elements [20]. The resolution is typically in the range of 0.1–1 nm.

3.4. Detector

The detector is responsible for capturing the emitted light from the plasma and converting it into an electrical signal for analysis. Common detectors include:

- **Charge-Coupled Devices (CCD)**: CCD detectors are widely used in LIBS systems due to their high sensitivity, wide dynamic range, and ability to capture spectra over a broad wavelength range. They provide high-resolution spectral data and are ideal for detecting weak emission lines from trace elements [21].
- **Photodiodes**: Photodiodes can also be used in specific applications where higher speed and time resolution are required. These detectors are typically faster than CCDs, but they provide lower resolution and sensitivity.

3.5. Sample Chamber and Environmental Conditions

The sample chamber plays a critical role in ensuring that the LIBS analysis is accurate and consistent. The environmental conditions within the chamber can affect plasma formation and spectral emission.

- **Ambient vs. Vacuum**: LIBS analysis can be performed under ambient conditions (air) or in a vacuum. Performing LIBS under vacuum conditions can reduce the effects of atmospheric interference (e.g., molecular absorption) and improve the sensitivity for certain elements. However, it requires specialized equipment and may not always be necessary for routine analyses [22]. Under ambient conditions, the background from air

or other gases can sometimes interfere with spectral lines, but the technique remains highly effective for most applications.

3.6. Portable and Person-Transportable LIBS Systems

The development of portable and field-deployable LIBS systems has significantly expanded the technique's applicability, especially in environmental monitoring, geology, and remote sensing. Portable LIBS systems are compact, lightweight, and often battery-powered, making them suitable for use in remote or challenging environments.

- **Miniaturization and Design**: These systems typically use lower-powered lasers and simplified optical components compared to traditional laboratory systems. Despite their compact design, portable LIBS systems can still achieve reliable analysis for a wide range of materials [23].
- **Applications**: Portable LIBS is used for on-site material analysis, such as in mining, archaeology, and hazardous waste management, where immediate results are crucial [24]. These systems are also employed in space exploration (e.g., Mars rovers), where traditional laboratory-based techniques are impractical.

4. Mechanism of Plasma Formation in LIBS

The mechanism of plasma formation in Laser Induced Breakdown Spectroscopy (LIBS) involves several stages, each critical to the formation, evolution, and analysis of the plasma. These stages include ablation, ionization, and cooling phases, which together contribute to the generation of spectral emissions that are analysed to determine the sample's elemental composition.

4.1. Stages of Plasma Evolution

4.1.1. **Ablation Phase:** The LIBS process begins when a high-energy laser pulse interacts with the surface of the sample. If the energy density of the laser exceeds the material's ablation threshold, it causes localized vaporization, melting, and removal of material from the sample surface. This material forms a plume of atoms, ions, and electrons [25]. The amount of material ablated depends on the laser pulse energy, wavelength, and the material's physical properties, such as density and heat capacity.

4.1.2. **Ionization Phase:** As the laser pulse continues, the ablated material is subjected to extreme heating, causing ionization. The ablation process generates a highly energized plasma composed of atoms, ions, and free electrons. The high temperature of the plasma (up to 10,000 K or more) causes the atoms in the plasma to undergo excitation and ionization, creating a plasma with a variety of charged species. The degree of ionization depends on the energy density of the laser pulse and the nature of the material being analysed [26]. The plasma in this phase is characterized by a mix of neutral atoms, singly charged ions, and free electrons. This stage is crucial because it dictates the spectral emission properties of the plasma, which are essential for identifying the elements present in the sample.

4.1.3. **Cooling Phase:** Following the ionization, the plasma undergoes rapid expansion and cooling. As the plasma cools, the excited species return to their ground states, releasing photons in the process. The emitted light consists of characteristic spectral lines corresponding to the elements in the sample. The cooling phase is critical for determining the temporal dynamics of plasma and spectral emissions, as different elements emit light at distinct wavelengths [27]. The cooling rate is influenced by factors such as the

plasma's density, size, and the ambient conditions. In this phase, the plasma's temperature decreases significantly, and the light emission becomes more distinct, which is analysed for elemental identification and quantification.

4.2. Spectral Analysis: How Light Emission Correlates with Elemental Composition

The spectral lines emitted during the cooling phase of plasma evolution are crucial for elemental analysis. Each element has a unique set of energy levels, and when the atoms or ions in the plasma return to their ground states, they emit photons at characteristic wavelengths. These spectral lines are used to identify the presence of specific elements in the sample [28]. The intensity of the emitted spectral lines is directly related to the concentration of the corresponding elements in the sample. By comparing the intensity of the spectral lines to calibration standards, quantitative analysis can be performed. The precision and accuracy of this analysis depend on the resolution of the spectrometer and the stability of the plasma during its evolution [29].

4.3. Role of Ambient Conditions

Ambient conditions, such as the gas environment and pressure in the sample chamber, play a significant role in the plasma formation and the quality of the spectral analysis.

4.3.1. Gas Environment: The composition of the surrounding gas influences plasma formation and cooling. When LIBS is performed in an air environment, the atmospheric gases (like oxygen and nitrogen) can interact with the plasma, affecting its temperature and the emission spectra. Using inert gases like argon or nitrogen in the sample chamber can reduce these interferences, leading to cleaner spectra and more accurate results [30].

4.3.2. Pressure: The pressure in the chamber also affects the dynamics of plasma formation. At lower pressures (e.g., in a vacuum), the plasma expands more rapidly, which can reduce the influence of molecular gases. High pressures can lead to quenching effects where the plasma cools rapidly, affecting the emission spectra and reducing sensitivity. Optimizing the pressure in the chamber is crucial for obtaining accurate and reliable measurements [31]. The combination of the laser parameters (e.g., energy, pulse duration) and the ambient conditions defines the overall behaviour of the plasma and the quality of the LIBS results.

5. Quantitative and Qualitative Analysis in LIBS

Laser Induced Breakdown Spectroscopy (LIBS) offers both quantitative and qualitative analysis of materials through the analysis of plasma-generated spectral emissions. Various techniques and approaches are used to enhance the accuracy and precision of these analyses, including calibration methods, data processing algorithms, and considerations regarding sensitivity and detection limits.

5.1. Calibration Techniques for Quantitative Analysis

5.1.1. Calibration-Free LIBS (CF-LIBS): Calibration-Free LIBS (CF-LIBS) is a method that aims to eliminate the need for standard reference materials or calibration curves. Instead, it uses fundamental models of plasma physics and spectral emissions to directly relate the plasma signal to the elemental concentration. CF-LIBS calculates the concentration of elements by using the ratio of the emitted line intensities to the continuum radiation, corrected for temperature and other plasma parameters [32]. This method is

advantageous because it simplifies the analysis process and can be applied to real-time, on-site measurements without the need for complex sample preparation or the use of calibration standards. However, it requires accurate knowledge of plasma behaviour and sophisticated models to account for varying plasma conditions. Despite these challenges, CF-LIBS has shown promising results in many applications, especially in industrial and environmental monitoring [33].

5.1.2. Standard Calibration Methods: In standard calibration-based LIBS, calibration curves are generated using known concentrations of elements. The intensity of spectral lines is measured for each standard sample, and a mathematical relationship between concentration and intensity is established. This calibration curve is then applied to unknown samples to determine their elemental composition. This technique is commonly used when precision is required, and it allows for accurate quantification of elements, especially in laboratory settings [34].

5.2. Algorithms for Data Processing and Spectral Deconvolution

The complexity of LIBS spectra, which often contain overlapping peaks from multiple elements, requires advanced data processing techniques. Spectral deconvolution algorithms help to resolve these overlaps and extract accurate information about the individual components.

5.2.1. Peak Fitting and Deconvolution: Spectral deconvolution is used to separate overlapping peaks and quantify individual spectral lines. Techniques such as Gaussian fitting, Lorentzian fitting, and more complex methods like Voigt profile fitting are commonly employed to extract precise information from spectra. These methods require sophisticated software tools that can model the spectral lines accurately and improve the overall resolution [35].

5.2.2. Multivariate Analysis: Advanced multivariate techniques, including Principal Component Analysis (PCA) and Partial Least Squares (PLS) regression, are used to handle the complexity of LIBS data. These methods reduce the dimensionality of large datasets and help identify the underlying patterns and correlations in the spectral data. PCA, for instance, can separate noise from signal and extract key features for better interpretation, while PLS can be used to predict elemental concentrations based on the spectral data [36]. These algorithms not only help in identifying and quantifying elements but also improve the robustness of the LIBS technique when dealing with real-world samples that may exhibit interference from matrix effects or environmental factors.

5.3. Detection Limits and Sensitivity Considerations

5.3.1. Detection Limits: The detection limit (DL) is a critical parameter in quantitative LIBS analysis, defining the smallest concentration of an element that can be reliably measured. The DL depends on various factors, including laser energy, plasma conditions, and the sensitivity of the spectrometer. Generally, LIBS is capable of detecting elements at concentrations as low as parts per million (ppm), but the exact detection limit varies depending on the matrix and experimental conditions [37]. Techniques such as the use of longer integration times or enhanced signal processing algorithms can improve the detection limit.

5.3.2. Sensitivity Considerations: The sensitivity of LIBS is influenced by the efficiency of the plasma generation, the ability of the spectrometer to detect weak signals, and the optimization of measurement parameters such as laser pulse duration and energy. High sensitivity is particularly important for trace analysis, where the concentration of elements is very low. Sensitivity can be improved by using higher laser energies, optimizing the spectrometer's resolution, and using more sensitive detectors like Charge-Coupled Devices (CCDs) [38]. Additionally, ambient conditions (such as pressure and gas type) and the sample matrix can significantly affect sensitivity. For instance, working in an inert atmosphere (e.g., argon) can help reduce interference from atmospheric gases, thus improving both sensitivity and precision in measurements [39].

6. Factors Influencing LIBS Performance

Laser Induced Breakdown Spectroscopy (LIBS) is highly sensitive to various factors that can affect the quality and accuracy of its results. These factors include laser parameters, sample properties, environmental conditions, and matrix effects. Understanding and optimizing these factors are crucial for improving LIBS performance across different applications.

6.1. Laser Parameters: Wavelength, Pulse Duration, and Repetition Rate

6.1.1. Wavelength: The wavelength of the laser plays a critical role in the excitation of the sample material. Different wavelengths interact with the material in various ways, influencing the efficiency of plasma generation and the subsequent emission spectra. Shorter wavelengths (e.g., UV lasers) can excite elements more efficiently and provide better signal-to-noise ratios for certain materials, while longer wavelengths (e.g., near-IR) might be used for less damaging interactions or specific applications. The optimal wavelength is typically selected based on the target element's ionization potential and the material's absorption characteristics [40].

6.1.2. Pulse Duration: The duration of the laser pulse affects the plasma formation and its characteristics. Shorter pulses (femtosecond or picosecond lasers) lead to more localized heating, which can result in finer and more controlled plasma formation. This is especially important in reducing the effect of matrix interferences and improving sensitivity in trace element analysis. Longer pulses (nanosecond lasers) are generally more commonly used in LIBS, as they allow for more extensive ablation and are easier to handle in conventional setups [41].

6.1.3. Repetition Rate: The repetition rate of the laser determines the frequency at which pulses are fired and influences the heating and cooling cycles of the plasma. High repetition rates can lead to higher signal intensities and faster sample analysis, but they may also increase the risk of sample overheating or matrix effects due to the buildup of heat in the sample. On the other hand, lower repetition rates reduce the risk of overheating but can lead to longer analysis times [42].

6.2. Sample Properties: Surface Texture, Homogeneity, and Composition

6.2.1. Surface Texture: The surface texture of the sample directly affects the ablation process. Rough or uneven surfaces can lead to inconsistent plasma generation, affecting both the spectral emission and

the reproducibility of results. Polished and flat surfaces are generally preferred, as they provide more uniform laser-material interaction, leading to more reliable measurements [43]. Additionally, laser-induced effects such as vaporization and the ejection of material from the surface can be influenced by the roughness of the sample.

6.2.2. Homogeneity: The homogeneity of the sample composition plays a significant role in LIBS analysis. Heterogeneous samples may result in varying spectral emissions due to localized differences in material composition, leading to inaccurate or inconsistent results. Homogeneous materials allow for more reproducible and precise measurements. For non-homogeneous samples, advanced calibration techniques or statistical methods may be used to account for these variations [44].

6.2.3. Composition: The elemental composition of the sample can influence the LIBS performance in multiple ways. The presence of certain elements or compounds can enhance or interfere with the emission signals of other elements. For example, the presence of high atomic number elements can suppress the emission of low atomic number elements through self-absorption or matrix effects. Calibration and spectral deconvolution techniques are often used to address these issues in complex matrices [45].

6.3. Environmental Factors: Temperature, Pressure, and Surrounding Gases

6.3.1. Temperature: The ambient temperature affects the ionization and excitation of the plasma, as well as the overall signal intensity. High ambient temperatures can increase the background signal and reduce the sensitivity of the LIBS system. Conversely, very low temperatures can affect the laser-material interaction and plasma stability. Temperature control is particularly important in precision applications like environmental monitoring or when dealing with volatile materials [46].

6.3.2. Pressure: The pressure of the surrounding environment can influence the characteristics of the plasma. LIBS is typically performed under atmospheric pressure, but in some cases, it may be conducted under low or high pressure to minimize interference from atmospheric gases or to enhance certain spectral features. For example, reducing atmospheric pressure can minimize spectral broadening caused by molecular species in the air, while increasing pressure can stabilize the plasma and improve the signal-to-noise ratio [47].

6.3.3. Surrounding Gases: The type of gas surrounding the sample also affects the plasma's properties. In atmospheric LIBS, the presence of air (composed mainly of nitrogen and oxygen) can cause spectral interferences or reduce the efficiency of plasma formation. Inert gases like argon or helium are sometimes used to suppress air-related interference and stabilize the plasma. Additionally, gas pressure can influence the cooling rate of the plasma and affect the intensity and lifetime of the emission signals [48].

6.4. Matrix Effects and Strategies to Minimize Matrix Effects

6.4.1. Matrix Effects: Matrix effects occur when the sample's matrix (the non-analyte material) interacts with the plasma or the emitted light, leading to signal

interference or distortion. These effects can be caused by factors such as sample composition, particle size, surface roughness, and ambient conditions. Matrix effects may lead to inaccuracies in elemental quantification or spectral interpretation, especially when dealing with complex materials like ores, soils, or biological samples [49].

6.4.2. Strategies to Minimize Matrix Effects: Several strategies can be employed to minimize matrix effects in LIBS analysis. One common approach is the use of internal standards, where a known amount of a reference material is added to the sample to help correct for matrix-induced variations. Additionally, advanced data analysis techniques, such as multivariate calibration and spectral deconvolution, can be used to distinguish matrix effects from the signals of interest. Laser parameters can also be optimized to reduce the impact of matrix effects by fine-tuning the pulse energy, laser focus, and repetition rate [50].

7. Applications of LIBS

7.1. Material characterization: LIBS is widely used for characterizing materials like metallurgy, ceramics, polymers, and alloys. It provides rapid and precise elemental analysis for quality control and material testing [51].

7.2. Environmental monitoring: In environmental science, LIBS is applied to analyse soil, detect water pollution, and assess air quality, offering a fast, non-destructive method for monitoring contaminants [52].

7.3. Biomedical analysis: LIBS plays a key role in biomedical applications such as tissue characterization and trace element detection, contributing to diagnostic tools for healthcare [53].

7.4. Industrial applications: In industries, LIBS is used for quality control, recycling processes, and failure analysis, allowing for efficient and accurate assessments of materials and products [54].

7.5. Space exploration: The Curiosity Rover's ChemCam utilizes LIBS for planetary exploration, analysing the composition of rocks and soil on Mars from a distance [55].

7.6. Forensic science and cultural heritage: LIBS aids in forensic investigations and the authentication of cultural artifacts, providing elemental analysis for dating and provenance studies [56].

8. Advantages of LIBS

8.1. Speed and real-time analysis: LIBS provides rapid, real-time analysis, enabling quick results without the need for complex sample preparation or lengthy processes [57].

8.2. Minimal sample preparation: One of the key advantages of LIBS is that it requires minimal or no sample preparation, making it highly efficient for various applications [58].

8.3. Capability to analyse almost any material: LIBS can analyse a wide range of materials, including solids, liquids, and gases, making it a versatile tool for diverse industries [59].

8.4. Portability for field applications: LIBS is inherently portable, allowing for on-site and field applications, such as environmental monitoring and space exploration [60].

9. Limitations of LIBS

9.1. Challenges in quantitative accuracy: While LIBS is effective for qualitative analysis, achieving high quantitative accuracy can be challenging due to factors like signal variability and calibration requirements [61].

9.2. Sensitivity to matrix effects: LIBS is sensitive to matrix effects, where the presence of other elements or compounds can interfere with the elemental signals, potentially affecting the accuracy of analysis [62].

9.3. Requirement of high-energy lasers: The need for high-energy lasers for plasma generation can be a limitation in terms of cost, equipment complexity, and energy consumption [63].

9.4. Need for extensive calibration in some scenarios: In certain applications, especially for quantitative analysis, LIBS requires extensive calibration and reference standards to ensure precise results [64].

10. Recent Technological Advancements

10.1. Innovations in laser sources and spectrometer technologies: Recent advancements in laser sources, such as fiber lasers and tunable lasers, have enhanced the efficiency and versatility of LIBS. Innovations in spectrometer technologies, including high-resolution spectrometers, have improved the precision and accuracy of elemental analysis [65].

10.2. Development of portable LIBS systems: Portable LIBS systems have been developed for on-site analysis, including compact handheld devices for field applications. These systems offer the convenience of in-situ measurements, benefiting industries like environmental monitoring and archaeology [66].

10.3. Advances in data processing and machine learning integration: The integration of machine learning and advanced data processing algorithms has enhanced LIBS' ability to handle complex data, improve spectral deconvolution, and automate the identification and quantification of elements, making LIBS more efficient and accurate [67].

11. Emerging Trends and Future Prospects

11.1. Role of AI and big data in enhancing LIBS applications: The integration of artificial intelligence (AI) and big data analytics into LIBS systems is revolutionizing data interpretation. AI algorithms are being used to enhance elemental detection, improve quantitative analysis, and streamline data processing, increasing LIBS' accuracy and efficiency [68].

11.2. Miniaturization and affordability of LIBS systems: There is a growing trend toward miniaturizing LIBS systems, making them more portable and cost-effective. This trend is driving the expansion of LIBS into industries and applications that were previously limited by equipment costs or size restrictions [69].

11.3. Expansion into new fields, such as pharmacology and nanotechnology: LIBS is beginning to find applications in emerging fields like pharmacology, where it is used for the analysis of pharmaceuticals, and nanotechnology, where it helps characterize nano-materials, providing rapid and precise elemental analysis [70].

11.4. Synergy with complementary techniques (e.g., Raman spectroscopy): LIBS is increasingly being used in combination with other analytical techniques, such as Raman spectroscopy, to provide complementary information. This synergy enhances the overall analytical power and accuracy of material characterization [71].

12. Case Studies

12.1. Application of LIBS in Lunar Surface Analysis - Chandrayaan Missions: Laser-Induced Breakdown Spectroscopy (LIBS) has revolutionized space exploration with its rapid and precise material analysis capabilities. Utilizing pulsed lasers at 1064

nm or 1030 nm wavelengths, LIBS was integral to India's Chandrayaan-3 mission. The Pragyan Rover's LIBS instrument analysed the moon's surface by creating plasma from laser-induced regolith, emitting characteristic light wavelengths. This enabled the identification of elements like magnesium, aluminium, silicon, potassium, calcium, titanium, and iron, offering valuable insights into lunar mineralogy and geological history. LIBS's non-contact, minimal-preparation technique proved vital for in-situ analysis, aiding Chandrayaan-3's study of the moon's south pole and potential resource deposits.[72,73]

12.2. **Real-world examples of LIBS applications:** One of the notable real-world applications of LIBS is its use in environmental monitoring. For instance, it has been used for on-site soil analysis to detect heavy metals and pollutants, providing immediate results without the need for sample transportation to a lab [74]. Another example is in the mining industry, where LIBS has been employed for rapid elemental analysis of ores, improving operational efficiency and resource management [75].

12.3. **Success stories in industries or research:** LIBS has also demonstrated success in the space exploration sector. The Curiosity Rover, equipped with a LIBS system, has been instrumental in analysing the composition of Martian soil and rocks, providing valuable insights into the planet's geology [76]. Additionally, in the field of forensics, LIBS has been successfully applied to the analysis of gunshot residue, offering a non-destructive, rapid method for forensic investigations [77].

13. CONCLUSION

Laser Induced Breakdown Spectroscopy (LIBS) has emerged as a powerful and versatile analytical tool with a broad range of applications. Its ability to analyse virtually any material with minimal sample preparation, real-time results, and portability has made it particularly valuable in diverse fields, from material characterization and environmental monitoring to space exploration and forensic science. Despite some challenges, including sensitivity to matrix effects and the need for extensive calibration, ongoing technological advancements in laser sources, data processing, and machine learning integration are continuously improving LIBS accuracy and applicability [78]. The transformative potential of LIBS is evident in its growing presence across various industries, with its expansion into new fields like pharmacology and nanotechnology marking significant milestones. As the technology becomes more affordable, miniaturized, and integrated with complementary techniques, LIBS is poised to revolutionize numerous sectors, providing rapid, non-destructive, and highly efficient analytical capabilities that will drive innovation and improve outcomes [79].

14. Research Gaps and Challenges

14.1. **Areas requiring further investigation:** Despite the progress made in LIBS, several research areas still require further exploration. One critical gap is improving the quantitative accuracy of LIBS, especially in complex matrices where matrix effects can significantly interfere with analysis. More research is needed to develop robust calibration-free methods and better algorithms for spectral deconvolution to enhance precision in diverse sample types [80]. Additionally, the integration of LIBS with advanced analytical methods like machine learning remains an evolving field, necessitating further investigation into

algorithm optimization and real-time data processing capabilities [81].

Limitations in current technologies and methodologies: Current LIBS systems still face challenges related to high energy consumption and the requirement for high-power lasers, which limit their widespread use, especially in portable and field-based applications. Moreover, the sensitivity of LIBS to environmental conditions (e.g., temperature and pressure) still poses significant limitations for consistent results in varying field environments. There is also a need for the development of cost-effective systems that maintain high performance, especially for small-scale and resource-limited settings [82].

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