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REAL TIME ANALYSIS WITH LASER INDUCED BREAKDOWN SPECTROSCOPY – A REVIEW

S. Marakatham*, A. Kavya, Harshita Padhi, B. Vineela B. Rajkamal

MALLA REDDY INSTITUTE OF PHARMACEUTICAL SCIENCES

Maisammaguda, Dhulapally, Kompally Post, Secunderabad – 500 100

Approved By AICTE, PCI, Affiliated to JNTU, Hyderabad.

ABSTRACT: Laser-Induced Breakdown Spectroscopy (LIBS) is a rapid, real-time analytical technique used to determine the elemental composition of solids, liquids, and gases. By focusing a high-energy laser pulse onto a sample, LIBS generates plasma and analyzes the emitted light to identify elements with minimal preparation. This includes LIBS principle, instrumentation, and sample preparation methods, highlighting its applications in environmental monitoring, industry, forensics, medicine, and space exploration. With its speed, versatility, and ability to detect multiple elements simultaneously, LIBS continues to be a valuable tool for modern scientific and technological advancements.

Key Words: LIBS, Laser-Induced Plasma, Elemental Analysis, Spectroscopy, Plasma Emission.

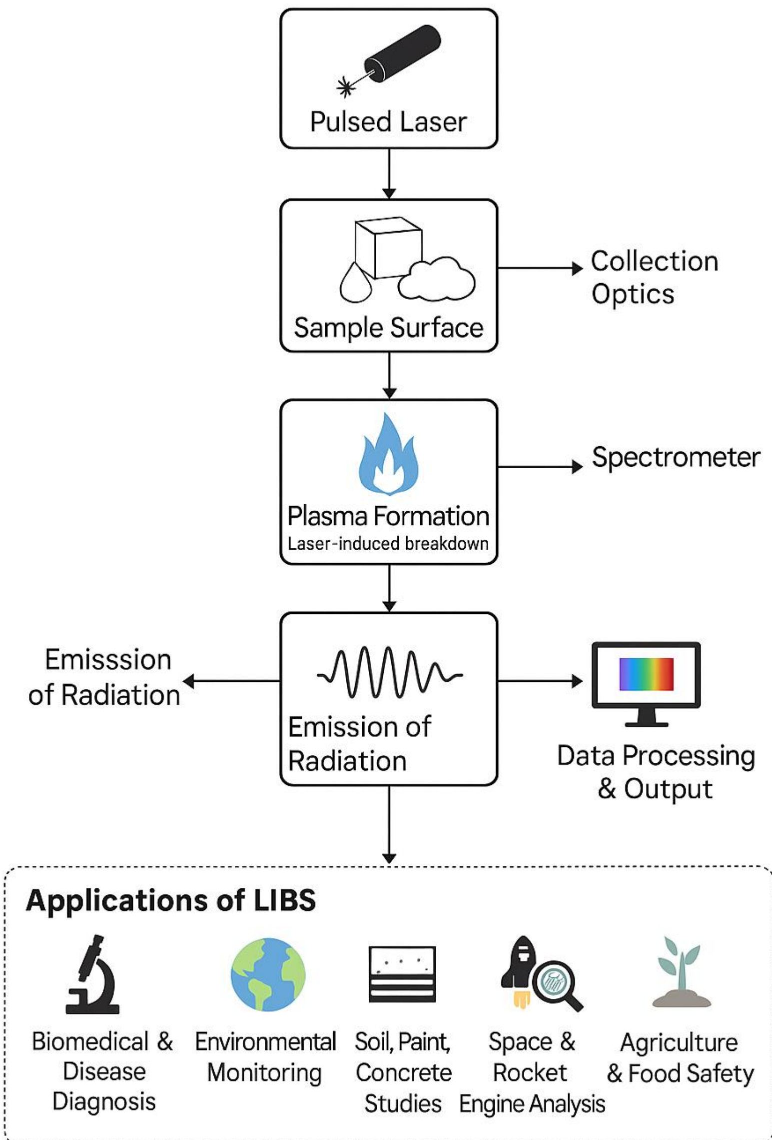

Fig 1: LIBS Graphical Representation

INTRODUCTION:

Laser-Induced breakdown spectroscopy (LIBS) is a potent analytical method for determining the elemental composition of biological specimens. Its rapid and sensitive analysis of solids, liquids, and gases has been driven by its straight forward implementation and minimal sample preparation requirements over the past three decades.

PRINCIPAL:

In LIBS, a pulsed laser beam is focused on the sample, creating a spark due to the intense electric field. This generates a high-density plasma that excites the atoms within the focal volume. The emitted atomic radiation is collected by a collimating lens and directed to the detection system. The intensity of the observed atomic emission lines in the LIBS spectrum is used to determine the concentration of the elements. As an emission technique, LIBS enables simultaneous multi-elemental analysis. This research has concentrated on developing and applying LIBS for monitoring RCRA metals in waste streams.

INSTRUMENTATION:

One of the salient features of this technique is the relatively simple instrumentation. In this technique, first pulsed laser light of sufficient intensity is focused on the sample to produce laser induced plasma (LIP) and then the emission intensities of the LIP are investigated. The essential components of any LIBS system are

a) A pulsed laser to ablate the sample and produce LIP,
b) Optics to route and focus the light from the laser to sample surface,
c) A lens to focus the light onto the sample surface,
d) Collection optics to collect the light emitted from the plasma,
e) A spectrograph to disperse the emitted light, and finally,
f) A detector camera to convert the emitted light into signal counts.

- **Source:** The basic purpose of a laser for LIBS is to produce sufficient and stable pulsed energy to generate the plasma. Pulsed laser energy depends upon laser wavelength and laser pulse width. Various lasers with wavelengths ranging from the infrared (IR) to UV regions of the spectrum have been used in LIBS. These include solid-state lasers such as the Nd:YAG laser; the ruby laser; gas lasers such as the CO2 laser; and the N2 laser; and excimer lasers. Nanosecond pulsed laser is most commonly used laser source. Parameters that influence laser induced plasma are laser wavelength, energy and pulse length

- **Fiber optic**: are used to focus laser on to the sample to create ablation as well as for collection of emitted radiation from the plasma towards the detectors
- **Detection system:**

  Spectrometers: Depending on spectral range, resolution and dispersion either Echelle or Czerny Turner can use. Spectrometer is used for diffraction of collected light from the plasma. Czerny Turner consists of two focal lenses to receive and focus diffracted light towards detector. Prism is used to diffract the collected light into different wavelength.

  Detectors: Two types of detectors used are Charge coupled detector (CCD) and Intensified Charge coupled detector (ICCD). CCD are less expensive but has less efficient resolution. ICCD are high resolution equipment with high cost.

METHODS OF MEASUREMENT:

1. The direction perpendicular to the incident laser's direction is where the plasma emission is collected. The gathered emission shows spatial dependence, which results in the loss of spectrum information regarding emission from the whole plasma plume, in addition to alignment challenges and decreased sensitivity.
2. In a different configuration, the collecting lens for plasma emission is the focusing lens itself. In this instance, the integrated value of radiation from all of the plasma's spatial positions is equivalent to the collected emission. A Q-switched, frequency doubled Nd: YAG laser (Continuum Surelite III) that produces an energy of 300 mJ at 532 nm with a 5-ns pulse makes up the LIBS experimental setup for solid sample research. With the use of a dichroic mirror and a quartz focusing lens with a 20 cm focal length, this laser was focused on the target while operating at 10 Hz. The optical emission from the LIP was collected using the same focusing lens and a dichroic mirror. Two quartz lenses of UV quality of focal lengths 100 and 50 mm were used to couple the plasma emission to an optical fiber bundle of 20 cm focal length. The combination of dichroic mirror and the same focusing lens (Fig. 1) was used to collect the optical emission from the LIP. Two UV-grade quartz lenses of focal lengths 100 and 50 mm were used to couple the plasma emission to an optical fiber bundle. The fiber bundle consists of 80 single fibers of 0.01

mm core diameter. The rectangular exit end of the optical fiber was coupled to the spectrograph.

Fig 2: Instrumentation of Laser Induced Breakdown Spectroscopy

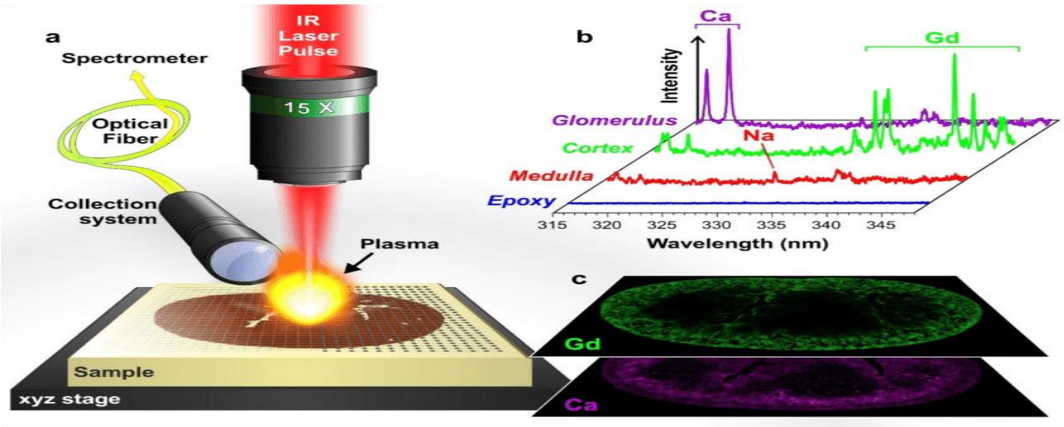

Table no 1: Merits and Demerits of LIBS

S.NO	Merits	Demerits
1.	**Versatile**: LIBS can analyze samples of almost any shape, size, and material	**Signal repeatability**: LIBS signals can have poor repeatability due to shot-to-shot fluctuations
2.	**Non-destructive**: LIBS is a non-destructive technique	**Limited sensitivity**: LIBS can have limited sensitivity
3.	**Rapid analysis**: LIBS can perform high-speed measurements	**Self-absorption**: Self-absorption can occur when emitted radiation is reabsorbed before exiting the source
4.	**Simultaneous analysis**: LIBS can analyze multiple elements at once	**Matrix effect**: Matrix effects can interfere with LIBS analysis
5.	**Stand-off analysis**: LIBS can be used for stand-off analysis, which is useful for online monitoring of industrial processes	

SAMPLE PREPARATION TECHNIQUES:

- ### SOLID SPECIMENS:

Certain solid specimens require no sample preparation for LIBS analysis, as they are naturally homogeneous and durable enough to withstand laser analysis. Examples include glass, metals, and polymers, while layered materials like paints and coatings can be analyzed directly or through depth profiling. However, in cases where deeper layers need examination, mechanical separation may be necessary.

Heterogeneous solids can often be analyzed without preparation using raster scanning or specimen rotation, depending on whether spatial or bulk analysis is required. However, some solid samples benefit from preparation to improve durability, sensitivity, and reproducibility. Without proper preparation, results may be qualitative, whereas thorough sample treatment can enable precise quantitative analysis, especially for complex materials like soils, rocks, or biological specimens.

REDUCTION OF MATRIX EFFECTS:

SEPARATION

One way to minimize matrix effects in LIBS analysis is by removing the matrix itself, though this can be challenging for many solid samples. If the analyte and matrix have differing solubility, separation becomes feasible-such as dissolving salts from sand and filtering the solution. For minerals, separation techniques like crushing, sieving, magnetic separation, or density-based methods help isolate components of interest. Sieving also reduces the "nugget effect," where large particles distort bulk composition. Alternatively, thin or thick petrographic sections can be prepared to expose mineral grains or fluid inclusions, enabling precise LIBS analysis.

DILUTION

When matrix removal is not feasible, dilution can be an effective alternative, especially if the analyte concentration remains high enough for detection. Dilution also helps when reference standards do not match the sample matrix. Ideal diluents should minimize matrix effects and be free of analytes or interfering elements. Some, like cellulose, wax, or graphite, also act as binders for pellet cohesion. For example, a blend of KBr, $CaCO_3$, and Al_2O_3 has been used for Pb, Cu, and Cr salt analysis, though spectral interferences must be considered. If dilution is impractical, matrix-matched calibration standards can be prepared using spiked and milled sand powders or plant-based "blank" matrices, ensuring accurate calibration for LIBS and related techniques.

INTERNAL STANDARD

Using an internal standard helps mitigate matrix effects, compensate for sample loss, and corrects instrumental variations. By normalizing analyte signals against a stable reference, internal standards enhance calibration linearity, precision, and spectral comparability. The choice of an internal standard depends on specimen type, instrument configuration, and emission characteristics. Ideally, both the internal standard and analyte should have similar ionization states and emission intensities. Some materials naturally contain suitable internal standards, such as Si in float glass, Ca in bones, or C in plant matter. For variable matrices like soil, an external internal standard may be required. Introducing the internal standard early in sample preparation ensures accurate corrections. While calibration-free LIBS methods exist, they generally provide lower accuracy and detection limits compared to well-prepared samples with internal standards.

FUSION

Fusion is a technique that transforms solid or liquid samples into glass disks by mixing them with a flux, such as lithium metaborate, at high temperatures. This process dilutes, homogenizes, and stabilizes samples for improved analytical accuracy. However, drawbacks include potential loss of volatile elements and spectral interferences from flux components like Li and B. Some studies have observed heterogeneity in fusion disks due to element settling during cooling, but overall, they have proven effective in reducing matrix effects. Compared to pressed pellets, fusion disks have shown better results for major and some trace elements in geological samples, though surface frosting may be required to enhance laser coupling.

PELLETS

Powders can be compressed into pellets for LIBS analysis, often requiring prior milling to ensure uniformity at a scale smaller than the laser spot size. If the powder lacks cohesion, a binder may be necessary to enhance pellet stability. Some binders also function as diluents, minimizing matrix effects. Studies have evaluated various binders, with KBr providing the highest ablation mass and signal enhancement for Mg, followed by starch. PVA produced the best-quality crater, making it a suitable alternative. Pelletization is also commonly used for plant materials, offering a reliable method for sample preparation in LIBS analysis.

- **LIQUID SPECIMENS:**

ADSORPTION METHOD

Adsorption is a widely used and cost-effective method for pre-concentrating metal elements in water samples. Various adsorbents, such as filter paper, wood slices, bamboo slices, graphite, bamboo charcoal, chelating resin, and fish bones, have been employed to enhance detection sensitivity and stability in liquid samples. Different adsorbents exhibit unique adsorption characteristics for specific elements.

Charcoal and ZnO have been effective in improving the limit of detection (LOD) for arsenic in groundwater, while bamboo charcoal, due to its microporous properties, has been used to detect trace levels of lead. Wood slices have been utilized to enrich trace lead in water samples, significantly enhancing LOD. Graphite allows for the rapid adsorption of heavy metals within minutes, making it suitable for real-time industrial wastewater monitoring. An automated method using graphite and LIBS has further improved heavy-metal enrichment, achieving LODs in the low parts per billion range, comparable to ICP-OES results. Chelating resins have also been applied for the rapid enrichment of cadmium in water, achieving high sensitivity.

Despite its advantages, adsorption has limitations, including the extent of enrichment and the single-use nature of substrates. Additionally, ensuring that adsorption materials remain uncontaminated with heavy metals.

MICRO-EXTRACTION

Micro-extraction relies on the interaction between analytes and extracting agents to achieve concentration. Dispersion liquid-liquid micro-extraction (DLLME) is a simple and cost-effective technique that provides a high enrichment factor and efficient extraction. It has been successfully used for LIBS analysis of metals in water, significantly improving sensitivity and lowering the limit of detection (LOD). DLLME has enhanced sensitivity by up to 32 times and reduced LODs by a factor of 22 for certain elements. It has also been applied to extract multiple metals, leading to a 4.0–5.5 times increase in sensitivity and a 3.7–5.6 times reduction in LODs.

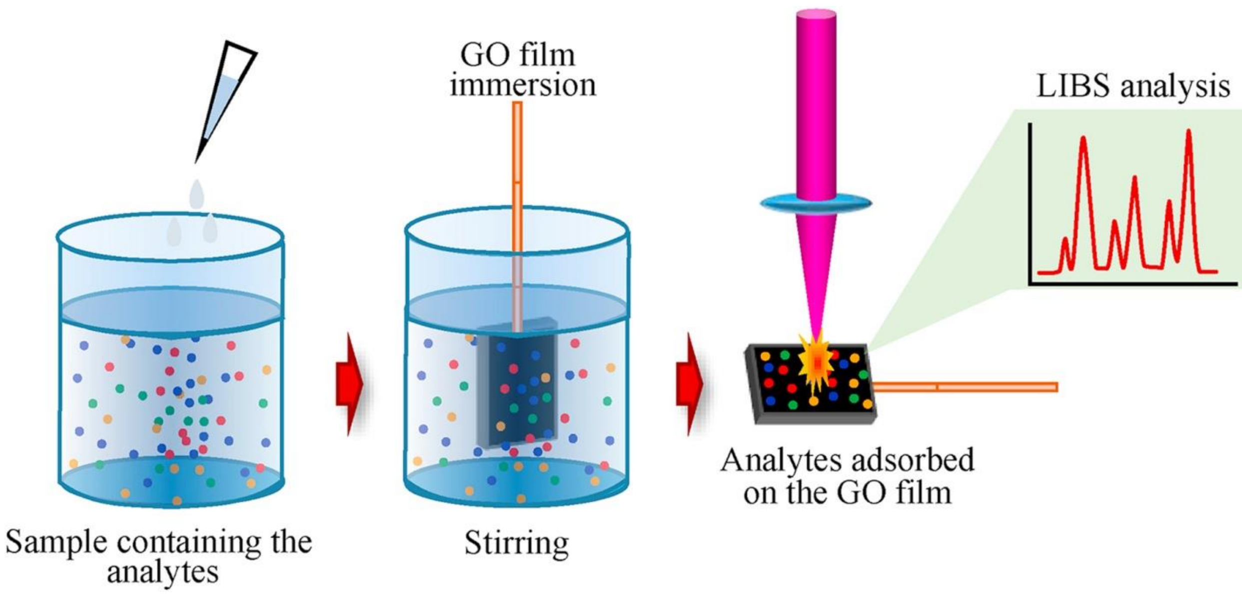

Fig 3: Thin Film Microextraction for trace elemental analysis of liquid samples using LIBS detection

Dispersive solid-phase micro-extraction (SPME) is another technique that aids in matrix conversion and concentration. This method has achieved low LODs for various metal ions, making it effective for trace element detection. While micro-extraction enhances the sensitivity of LIBS analysis and reduces LODs, it has limitations related to extraction efficiency and potential interference from other ions.

FREEZING

Freezing liquid into ice is a direct pretreatment technique that transitions the sample from liquid to solid, improving analytical performance. Ice ablation minimizes splashing and agitation, enhancing the stability of LIBS analysis. Studies have shown that LIBS signals are significantly improved in ice samples compared to liquid, with the limit of detection (LOD) being approximately six times lower.

Quick freezing techniques have been used to quantitatively assess metal elements in water, achieving LODs in the parts per million range. However, LIBS analysis must be conducted before the ice melts, requiring specific freezing methods, such as liquid nitrogen, to maintain sample integrity.

LIQUID-TO-SOLID MATRIX CONVERSION

Several methods have been developed for converting liquid solutions into solid-matrix samples for LIBS analysis. One approach involves using calcium oxide (CaO) to generate calcium hydroxide ($Ca(OH)_2$), which is then compacted into pellets for detecting metals like Cr, Pb, Cd, and Zn in aqueous solutions. Another technique converts liquid oil into solid tablets through a two-step distillation process, followed by heating and molding the solid paste. Similarly, heavy liquid residues, such as petroleum crude oil, can be solidified into asphaltene tablets by mixing with n-heptane, heating, cooling, filtering, and pressing the dried material into pellets.

Other efficient liquid-to-solid transformation methods include drying microdroplets on an aluminum substrate, enhancing LIBS signals through surface-enhanced LIBS. Additionally, metal precipitation combined with membrane separation has been used for rapid sample preparation. In cases where solids are suspended in liquids, simple filtration and drying of the residue provide a straightforward approach for LIBS analysis.

CONVERTING LIQUID INTO AEROSOLS

Transforming liquids into aerosols enhances sample stability, leading to more consistent LIBS signals. Various techniques have been developed to achieve this. One method involves using a nebulizer and dryer to generate submicron-sized aerosols, enabling fast and sensitive real-time detection of toxic metals in water. Another approach utilizes a microhole array sprayer, significantly reducing the relative standard deviation (RSD) and improving analysis precision.

Converting water samples into aerosol particles by introducing NaCl has been shown to enhance trace metal concentrations, achieving low limits of detection (LODs) for elements like Pb and Zn. Electrodynamic balancing technology has also been employed to capture charged droplets and convert them into dried aerosol particles for precise LIBS analysis, achieving LODs in the milligram per liter range.

Additionally, hydride generation LIBS (HG-LIBS) has been used to detect elements such as Sn, As, Sb, Pb, and Ge by extracting them as gaseous hydrides before atomization. However, this method is limited to elements capable of forming covalent hydrides.

APPLICATIONS:

- **INDUSTRIAL APPLICATION**

LIBS are widely used in industrial process monitoring due to its capability for rapid and remote analysis. It is particularly useful in environments with high temperatures, corrosive materials, or radioactive substances, where human access is challenging. LIBS can be integrated with compact devices to optimize sample positioning and focus adjustment, making it highly suitable for industrial applications, especially in the metallurgical sector.

In geology, LIBS addresses two main challenges: in situ mineral identification and trace element analysis in rocks. It is also utilized in various fields, including space exploration for analyzing extraterrestrial materials, defense for detecting explosives and biological agents, and nuclear applications for identifying and quantifying uranium and other metals. Studies have demonstrated its effectiveness in detecting and quantifying elements such as nickel, iron, cobalt, copper, magnesium, sulfur, and manganese in various samples, including ores and aqueous solutions.

- **ENVIRONMENTAL MONITORING**

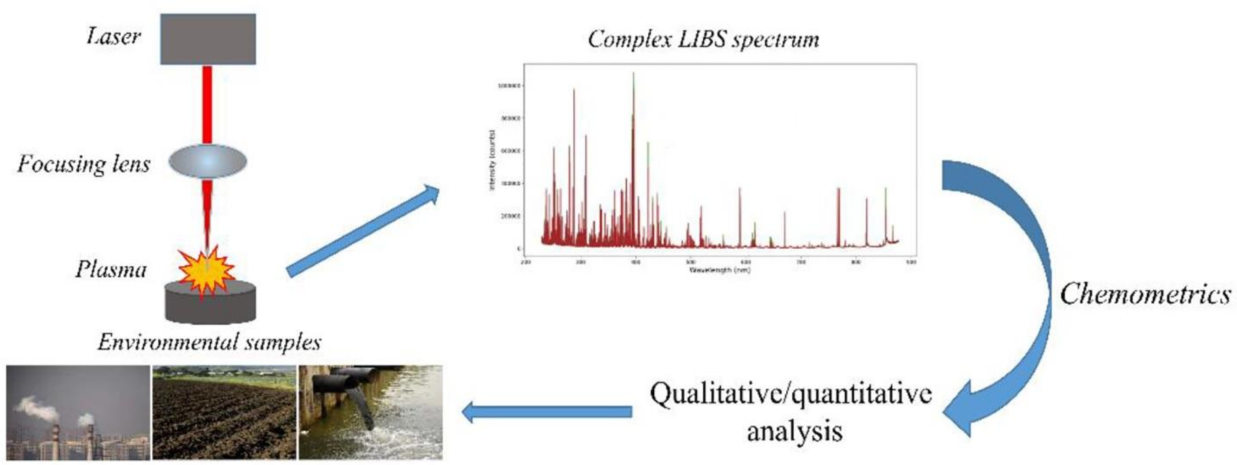

Fig 4: Application of laser-induced breakdown spectroscopy (LIBS) in environmental monitoring

OFF-GAS EMISSION

LIBS is an effective technique for real-time monitoring of hazardous and toxic trace elements in off-gas from waste processing systems, ensuring public health safety. By directing a laser beam onto the gas stream and capturing optical emissions, LIBS enables rapid detection of toxic metals.

It has been used for online detection of lead (Pb) aerosols, achieving a detection limit of 155 $\mu g/m^3$. Additionally, LIBS has been integrated into waste remediation processes, reducing toxic metal emissions in plasma torch facilities. The use of metal hydrides for calibration has shown that gas composition, pressure, and laser intensity influence detection accuracy.

For LIBS to function as a continuous emission monitor (CEM), it must provide quantitative trace-level analysis. A system has been developed for near real-time monitoring of toxic metals, successfully detecting Beryllium (Be) and Chromium (Cr) at all levels, Cadmium (Cd) at medium and high concentrations, and lead (Pb) at high concentrations. However, further improvements in sensitivity are needed for monitoring Mercury (Hg), Arsenic (As), and Antimony (Sb).

STUDY OF SOIL, CONCRETE, AND PAINT

LIBS play a crucial role in detecting contamination in soil and concrete for environmental applications. A portable LIBS system has been used to identify toxic metals in soil, with detection limits recorded for Ba, Be, Pb, and Sr. Remote detection using an optical fiber probe has also been successful in identifying Ba and Cr in soil samples.

Matrix effects have been observed in LIBS analysis, influencing detection limits and precision. The accuracy of LIBS measurements depends on proper calibration, as variations in chemical speciation and matrix composition can affect results. In concrete analysis, LIBS has been applied for Pb detection, using a time-resolved spectrum for quantitative assessment. The absolute Pb signal remained stable across a specific laser pulse energy range. Additionally, LIBS has been demonstrated as an effective tool for detecting Pb in paint, highlighting its potential for assessing environmental health risks.

STUDY OF RADIOACTIVE ELEMENTS

LIBS has been employed for monitoring radioactive elements in process streams, demonstrating its effectiveness in detecting uranium in solution with a detection limit of 100ppm. It is preferred over traditional radiological measurement methods, as nuclear detectors may struggle to differentiate between radionuclides like U, Pu, and Np. LIBS spectra have been used to identify suitable emission lines for detecting these elements, making it a valuable tool for analyzing radioactive waste streams.

Additionally, LIBS has been applied in nuclear power facilities to assess radiation embrittlement by measuring copper levels in A533b steel. Since copper is a key impurity contributing to embrittlement, its concentration can serve as an indicator of material degradation and expected lifespan.

- ## BIOLOGICAL AND BIOMEDICAL APPLICATIONS

LIBS play a crucial role in analyzing the elemental composition of various biological and biomedical samples, including calcified tissues, pharmaceuticals, plants, seeds, and fruits. It provides a rapid and efficient alternative to conventional analytical methods.

In dentistry, LIBS is used to differentiate between healthy and carious teeth by detecting elements such as Ca, P, Mg, Cu, Zn, Sr, H, and O. It also allows for precise identification of various regions. Additionally, LIBS facilitates the morphological and atomic-level examination of kidney stones, aiding in the selection of suitable edible salts for kidney patients. The technique has also shown promise in diabetes management through quantitative elemental analysis.

LIBS simplify the analysis of plant samples by eliminating the need for complex acid digestion procedures. It enables rapid assessment of micronutrients, antioxidants, and toxic elements in plants, seeds, fruits, leaves, and roots. It has been successfully used to detect elements in medicinal plants like Emblica Officinalis, Cynodon dactylon, and Momordica charantia, as well as trace silicon deposition in Saccharum species. Studies have also shown its ability to measure lead accumulation in wheat seedlings, with higher concentrations found in the roots.

In the food industry, LIBS is valuable for detecting toxic elements in food products at trace levels, ensuring safety and regulatory compliance. It has been used to analyze elemental concentrations in wheat seeds, assess impurities in ice balls of different colors, and quantify elements in various food supplements.

- **FORENSIC APPLICATION:**

Laser-Induced Breakdown Spectroscopy (LIBS) is a powerful forensic tool for rapid and non-destructive elemental analysis of physical evidence. It has been effectively applied to forensic investigations involving counterfeit currency, explosives, drugs, gunshot residues, inks, and fingerprints. The technique enables simultaneous multi-element detection with minimal sample preparation, making it useful for in-field analysis. LIBS is particularly advantageous in forensic glass analysis, where trace elements can distinguish sources of broken glass found at crime scenes. In addition, LIBS assists in ink and paper authentication, helping to detect forgeries and alterations in documents. It also plays a crucial role in gunshot residue detection, offering quick results that link suspects to firearm usage. Moreover, LIBS has been explored for latent fingerprint visualization by mapping sodium and other trace elements deposited from human skin. Its ability to analyze paint layers and coatings enhances hit-and-run investigations. Overall, LIBS has great potential to complement traditional forensic methods, improving the accuracy and efficiency of criminal investigations.

- **QUALITATIVE ANALYSIS:**

LIBS is a powerful technique that enables the detection of all elements in a sample using a single nanosecond laser pulse. However, for accurate detection, the element concentration should typically be in the parts per million (ppm) range or higher. This method is widely used in applications where it is crucial to confirm the presence or absence of specific elements. For example, in **toys**, LIBS helps ensure that hazardous elements like mercury (Hg) do not exceed safe limits, while in food safety**,** it verifies the presence of essential nutrients like magnesium (Mg) and iron (Fe). Beyond simple detection, LIBS also enables quantitative elemental analysis**,** determining the precise concentration of elements in ppm, their absolute mass in nanograms, or their surface concentration in nm/cm^2.

This can be achieved through two main approaches: Calibration curve LIBS, which relies on reference standards, and Calibration-free LIBS (CF-LIBS)**,** which eliminates the need for external calibration. Researchers in India have made significant advancements in both these methodologies, further enhancing the accuracy and applications of LIBS in various fields.

- **DISEASE DIAGNOSIS:**

LIBS has proven to be a valuable tool in medical diagnostics, offering rapid and non-invasive elemental analysis of biological tissues, fluids, and other samples. In cancer detection, LIBS can differentiate between healthy and cancerous tissues based on variations in elemental composition. Cancerous tissues often exhibit higher concentrations of calcium (Ca), magnesium (Mg), and other trace elements due to abnormal cell activity and calcification processes. For instance, LIBS has been successfully used to analyze breast cancer**,** liver cancer**,** and skin cancer, providing a potential alternative to traditional biopsy methods. The ability to perform real-time analysis allows for quicker diagnosis, reducing the need for extensive laboratory testing.

Apart from cancer, LIBS is also effective in diagnosing kidney stones and gallstones, which are formed due to mineral imbalances. By analyzing the composition of these stones, doctors can determine their origin and suggest preventive measures to avoid recurrence. Similarly, LIBS is useful in monitoring osteoporosis, where a reduction in calcium levels in bones is a key indicator of disease progression. Studies have also explored the use of LIBS in detecting thyroid disorders by analyzing trace elements in nails and hair, as these tissues reflect long-term metabolic changes. The technique has shown promising results in identifying diabetes, hyperthyroidism, and liver fibrosis, all of which involve specific elemental imbalances in the body.

- **SURGICAL ASSISTANCE AND LASER-GUIDED OPERATIONS:**

One of the most advanced applications of LIBS is its use in laser surgery and real-time tissue differentiation. During surgical procedures, especially in neurosurgery, dermatology, and orthopedics, distinguishing between different tissue types is crucial to avoid unnecessary damage. LIBS help by providing instant feedback on tissue composition, allowing surgeons to identify nerves, bones, and soft tissues accurately. In brain surgery, LIBS can differentiate between cancerous and non-cancerous brain tissues, helping in the precise removal of tumors without harming healthy brain matter.

In dermatology**,** LIBS is widely used in procedures such as tattoo removal**,** skin lesion ablation, and hyperkeratosis treatment. By analyzing the elemental composition of different skin layers, doctors can ensure controlled removal of the affected area while preserving healthy tissue. Similarly, in dentistry, LIBS plays a crucial role in cavity detection and enamel preservation. Dental caries lead to a loss of calcium and phosphorus in tooth enamel, which can be detected using LIBS. This enables dentists to remove only the decayed portions, ensuring minimal damage to the natural tooth structure.

LIBS is also being integrated into robotic surgical systems, where it serves as a guide for laser-based cutting tools. By analyzing the plasma emissions generated during laser ablation, these systems can adjust their settings dynamically, ensuring precise and safe surgical outcomes.

- **VETERINARY MEDICINE:**

LIBS is not only beneficial for human healthcare but also plays a vital role in animal health and veterinary science. It is widely used in livestock management to monitor essential minerals in animal feed and tissues. Deficiencies in elements like magnesium (Mg), iron (Fe), and calcium (Ca) can lead to severe health problems in animals, affecting their growth and productivity. LIBS enables rapid assessment of these nutrients, allowing veterinarians to make dietary recommendations for livestock.

In forensic veterinary science, LIBS helps in determining the cause of death in animals by analyzing skeletal remains and tissues. It can detect traces of toxic heavy metals such as lead (Pb), arsenic (As), and mercury (Hg), which may indicate poisoning or environmental contamination. Additionally, LIBS has been employed in detecting bacterial and viral infections in animals, making it a valuable tool for disease control in farms and wildlife conservation efforts.

- **PATHOGEN DETECTION:**

LIBS has emerged as a powerful tool in microbiology and pathogen detection. It enables the rapid identification of bacteria, viruses, and other microorganisms by analyzing their unique elemental signatures. This application is especially crucial in clinical diagnostics, where quick detection of infectious agents can lead to timely treatment. LIBS has been successfully used to identify bacterial contamination in medical samples, airborne pathogens in hospitals, and bioaerosols in environmental settings.

- **GEOLOGICAL AND EXTRATERRESTRIAL APPLICATION:**

Laser-Induced Breakdown Spectroscopy (LIBS) is an advanced analytical technique used for real-time, on-site elemental analysis of geological and extraterrestrial materials. It requires no sample preparation, is nearly non-destructive, and functions effectively in various environments such as air, argon, and vacuum. LIBS plays a crucial role in geological applications by enabling the detection of trace elements in rocks, soil, and water. It has been used for meteorite analysis to determine elemental composition and in soil contamination studies to assess heavy metal levels like cadmium, which pose environmental and health risks. In extraterrestrial applications, a compact and portable LIBS system has been designed for planetary exploration to analyze lunar regolith and surface materials. This system consists of an Ablation Unit (AU), Plasma Emission Detection Unit (PEDU), and Processing Unit (PU) and has undergone rigorous environmental testing to ensure functionality under extreme conditions. LIBS has also been applied to study minerals that could support microbial life in extreme environments, providing insights into planetary habitability. Additionally, spectroscopic analysis of impact-generated materials has helped in understanding meteorite collisions and surface compositions. As a versatile tool, LIBS continues to contribute significantly to planetary research by enhancing the understanding of elemental compositions and environmental conditions in space and on Earth.

- **LIBS IN SPACE RESEARCH:**

Rocket engine health monitor

Laser-Induced Breakdown Spectroscopy (LIBS) plays a crucial role in monitoring the health of rocket engines by detecting trace metallic components in the exhaust plume of hydrocarbon-fueled engines. Identifying these elements provides early indications of wear and corrosion in engine materials, allowing for preventive measures before major failures occur. Catastrophic engine failures are often preceded by bright optical emissions caused by metal erosion from engine parts, which occur due to the high temperatures in the rocket plume leading to partial vaporization and atomic emissions. Studies have demonstrated LIBS' effectiveness in detecting metal traces, such as copper, in the ignition chamber and throughout the fuel plume. Observations indicate that measurements taken away from the luminous zone of the plume provide more valuable insights into the engine's condition.

Probe for Mars expedition

LIBS has also been explored for Mars exploration, particularly for remote geological analysis. It has been designed to operate from distances of up to 20 meters, detecting at least 10 elements in rocks and dust with high sensitivity, crucial for determining their origins. Experiments under simulated Martian atmospheric conditions have shown accurate detection of various elements, despite challenges in calibration due to bulk matrix effects. The Mars 2020 mission incorporates LIBS technology within the SuperCam instrument suite, which includes additional imaging systems to analyze Martian soil and rocks. Furthermore, the SuperCam is equipped with a microphone to capture the acoustic signal generated by the laser interaction with Martian rocks, providing further insights into surface composition. LIBS continues to prove its significance in both aerospace engineering and planetary exploration by enabling precise, real-time elemental analysis in extreme environments.

- **LIBS IN ARCHEOLOGY SEARCH:**

Laser-Induced Breakdown Spectroscopy (LIBS) is a valuable tool for analyzing archaeological samples and cultural artifacts, particularly when traditional methods pose risks of damage or require complex sample preparation. Portable LIBS devices allow for on-site analysis, eliminating the need to transport delicate artifacts. Additionally, LIBS is a non-contact technique, ensuring that valuable historical objects remain unharmed during analysis. It is widely used to determine the elemental composition of various materials, including painted artworks, icons, polychromes, sculptures, pottery, weaponry, and artifacts made from metals, glass, and stones. Beyond analysis, LIBS also aids in the restoration of artworks by selectively removing microscopic amounts of material, which is useful in conservation efforts. In paintings, it enables pigment identification, assisting in the dating and authentication of frescoes and artworks. Moreover, LIBS can be combined with other techniques, such as Raman spectroscopy and X-ray fluorescence (XRF), to enhance analytical accuracy and provide a more comprehensive understanding of cultural heritage materials. This capability makes LIBS an essential tool for archaeologists and conservationists, offering precise, non-destructive, and real-time elemental analysis.

REFERENCES:

1. Jantzi SC, Motto-Ros V, Trichard F, Markushin Y, Melikechi N, De Giacomo A. Sample treatment and preparation for laser-induced breakdown spectroscopy. *Spectrochim Acta Part B At Spectrosc.* 2016;115:52–63.
2. Suyanto H, Nasution AMT, Trisnawati NLP, Suprihatin IE. Deposition-pellet preparation technique for powder samples measurement using laser-induced breakdown spectroscopy. *Instrum Mesure Métrol.* 2022;21(4):139-144.
3. Zhang Y, Zhang T, Li H. Application of laser-induced breakdown spectroscopy (LIBS) in environmental monitoring. *Spectrochim Acta Part B At Spectrosc.* 2021;181:106218.
4. Bauer AJR, Buckley SG. Novel applications of laser-induced breakdown spectroscopy. *Appl Spectrosc.* 2017;71(4):553–566.
5. Guo L, Zhang D, Sun L, Yao S, Zhang L, Wang Z, Wang Q, Ding H, Lu Y, Hou Z, Wang Z. Development in the application of laser-induced breakdown spectroscopy in recent years: A review. *Front Phys.* 2021;16(2):22500.
6. H. Sobral, R. Sangin´ es, A. Trujillo-V´ azquez, Detection of trace elements in ice and water by laser-induced breakdown spectroscopy, Spectrochim.
7. F.F. Al-Adel, M.A. Dastageer, K. Gasmi, M.A. Gondal, Optimization of a laser induced breakdown spectroscopy method for the analysis of liquid samples, J. Appl. Spectrosc.
8. J.L. Tarazona, J. Guerrero, R. Cabanzo, and E. Mejía-Ospino, Construction of a predictive model for concentration of nickel and vanadium in vacuum residues of crude oils using artificial neural networks and LIBS, Appl. Opt., 51 (2012) B108-B114.
9. A. De Giacomo, M. Dell'Aglio, A. Casavola, G. Colonna, O. De Pascale, and M. Capitelli, Elemental chemical analysis of submerged targets by double-pulse laser induced breakdown spectroscopy, Anal. Bioanal. Chem., 385 (2006) 303-311.
10. S.T. J¨ arvinen, J. Saarela, J. Toivonen, Detection of zinc and lead in water using evaporative preconcentration and single-particle laser-induced breakdown spectroscopy, Spectrochim. Acta Part B 86 (2013) 55–59.
11. S. Ünal, S¸. Yalçın, Development of a continuous flow hydride generation laser- induced breakdown spectroscopic system: determination of tin in aqueous environments, Spectrochim. Acta Part B 65 (2010) 750–757.
12. Mputu Kanyinda Jean-Noël, Kaniki Tshamala Arthur, Baele Jean-Marc. *LIBS Technology and its Application: Overview of the Different Research Areas.* Journal of Environmental Science and Public Health, 2020; 4(3): 134-149.
13. Rai, V. N., & Thakur, S. N. *Instrumentation for LIBS and Recent Advances.* In Laser-Induced Breakdown Spectroscopy (Chapter 5). Elsevier, 2020.
14. Tarai, A. K., Junjuri, R., & Gundawar, M. K. *Advances in Applications of LIBS in India: A Review.* Asian Journal of Physics, Vol. 30, No. 6 (2021), pp. 871-888.
15. Hark, R., & East, L. J. (2014). Forensic applications of LIBS. *Springer Series in Optical Sciences*

16. Gaudiuso, R., Melikechi, N., Abdel-Salam, Z. A., Harith, M. A., Palleschi, V., Motto-Rose, V., & Busser, B. (2018). Laser-induced breakdown spectroscopy for human and animal health: A review. *Spectrochimica Acta Part B.*