



Optical Spectroscopic and Plasma Diagnostics of *Moringa oleifera* Using Laser-Induced Breakdown Spectroscopy

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Abstract

The spectroscopic and plasma characteristics of *Moringa oleifera* were examined by laser-induced breakdown spectroscopy (LIBS) and optical emission spectroscopy (OES) at laser energies between 50 and 450 mJ. On compressed *Moringa oleifera* powder discs, laser-induced plasma was produced and was analyzed to determine elemental composition as well as plasma parameters. There were distinct emission lines of K, Ca, Na, and O at higher intensities with laser power. Based on Boltzmann plot analysis, we observed a change from a value of 1.298 electron temperature (T_e) to 1.352 eV which was an increase in electron temperature (T_e) and reflected the improved efficiency of excitation as well as plasma stability. The majority of the analysis was validated through Lorentzian fitting and Stark broadening thus, thus, allowing for quantitative evaluation electron density. The findings validate local thermal equilibrium condition and exhibit the suitability of LIBS/ OES to plant-based material characterization and green nanotechnology usage.

Keywords: *Moringa oleifera*, Optical Emission Spectroscopy, Lorentzian fitting and Stark broadening.

1. Introduction

Due to its rich phytochemical contents, biocompatibility, and numerous biological and environmental applications, *Moringa oleifera* has attracted much scientific interest. Furthermore, recently, the introduction of spectroscopic methods with laser-matter interaction has opened new perspectives to study the elemental and molecular structure of plant-based materials with high precision. Among these methods, laser-induced breakdown spectroscopy (LIBS) has received considerable attention as a fast, nondestructive, and exceedingly sensitive analytical method for investigating biological samples, such as medicinal plants like *Moringa oleifera*^{1,2}. After a high-energy laser pulse interacts with the *Moringa* sample, a transient plasma plume is created above the surface that emits characteristic radiation corresponding to excited atomic and ionic species present in the material. The spectra released yield useful data on elemental content, plasma temperature, electron density, and excitation response, which make LIBS a rich tool for qualitative and quantitative analysis of plant materials^{3,4} at this stage. Most particularly, emission lines visible about 500 nm, often attributed to Ca, Mg, and organic molecular fragments, should be used to interpret the stability and the excitation efficiency of plasma at different laser energies⁵. The shape and width of the spectral emission lines is very important in plasma diagnostics. In examining spectral profiles, Lorentzian fitting is well-established since it reveals collisional and Stark broadening mechanisms dominant in dense laser-driven plasmas⁶. Differences in peak intensity and FWHM with increased laser energy unambiguously correlate with fluctuations in plasma electron density and temperature, permitting accurate characterization of laser-sample coupling and plasma evolution⁷. This is necessary for improved experimental conditions and reproducibility of plant-based LIBS studies. Besides elemental characterization, spectroscopic characterization of *Moringa* is becoming more and more

important to biomedical studies. When *Moringa* extracts are synthesized alongside nanomaterials or plasma treatment, they have been demonstrated to possess enhanced antimicrobial activity, antioxidant behavior, and synergistic effects. Hence, characterization of *Moringa* optical emission response to varying laser energies is not only essential for analysis but also a key issue for realization of *Moringa* applications in plasma medicine, green nanotechnology, and bio functional materials. In this work, we have set an objective for the emission spectra of *Moringa oleifera* using laser-induced plasma at several laser energies, using Lorentzian fitting for selective extraction of the plasma parameters and for the evaluation of stable plasma performance^{8,9}. The findings present fresh information about laser effects on plant interaction and facilitate the application of spectroscopic plasma diagnosis techniques for bioactive plant material identification tools.

1.1. Theory

LIBS can be applied to solids, liquids, and gases^{9, 10}. Plasma light emitted by ionization and ablation of a sample material under laser pulse irradiation is detected by means of a spectrometer and detectors^{11, 12}. Properties of emission lines, including breadth, forms, and shifts, can be employed to derive information, including temperature and electron density, from the emitted plasma spectrum¹³⁻¹⁷. The Boltzmann plot technique was used in this study/research: the measured temperature of generated plasma is an important parameter since it can be used to describe the properties of plasma substances. The procedure is frequently used in LIBS for recording the plasma temperature using the Boltzmann plot. This technique is primarily used in applications involving atomic and electronic spectra of plasma systems, such as thermal plasma temperature profiling. The idea at work with this method is based on the theory of the Boltzmann distribution, which shows the distribution of atoms and ions at different energy levels in a thermal system at equilibrium. Application of the Boltzmann method: Collection of spectral information to measure the intensity of the spectral lines for certain transitions between energy levels of the atoms or ions of the sample. For each spectral line in the sample, the energy levels are assigned from spectral tables or databases. The application of the Boltzmann equation, which relates the intensity of the spectral lines (I) from the number of atoms in an energy level to the temperature. This technique is shown as the average temperature(T), or plasma on average temperature determined by this method. **Equation 1** is utilized¹⁷⁻¹⁹:

$$\ln(I\lambda/gA) = -E/(kTe) + C. \quad (1)$$

Where I is the intensity of the spectral lines and g is the weight (statistical).

A (transition probability), λ (wavelength), E (excited state energy), K (Boltzmann constant). In the subsequent steps of spectral line ionization, the standard Saha–Boltzmann equation is considered. It is given as²⁰:

$$n_e = 6.04 \times 10^{21} \times \frac{I_1}{I_2^*} (10)^{\frac{3}{2}} e^{\frac{(E_1-E_2-X_z)}{KT}} \text{ cm}^{-3} \quad (2)$$

$$\text{Where: } I_2^* = \frac{I_2 \lambda_2}{g_2 A_2} \quad (3)$$

Where: Xz denotes the ionization potential of the organism at the second ionization level, expressed in eV. The line intensities for the transition from higher level 2 to lower level 1 is denoted by I2. The symbol λ represents the acceptable wavelength of transition between level 2 and level 1. g2 represents the statistical contribution of the transition from level 2 to level 1, A2 represents the changes in probabilities and z represents the stage of ionization of the categories indicated above^{21,23}. Although, the frequency of plasma generated $f_p \propto \sqrt{n_e}$; higher electron density gives higher plasma frequency. can be found using the equation^{24,25}:

$$f_p = 8.98 \sqrt{n_e} \text{ Hz} \quad (4)$$

Equation 4 is valid when ne is expressed in cm^{-3} and fp in Hz.

Plasmas generally have a primary property related to their frequency, which is determined solely by their density. Typically, a small ne results in an extremely high level of plasma frequency²¹⁻²³. Plasma's quasi-neutrality is attributed to Debye shielding (λ_D), in which there are charges in

the particles that shield them from neighboring electric fields. A distance λ_D determines the length of the Debye^{26,28}:

$$\lambda_D = \sqrt{\frac{\epsilon_0 K_B T_e}{e^2 n_e}} = 7.43 \times 10^2 \sqrt{\frac{T_e}{n_e}} \quad (5)$$

where:

λ_D : Debye length (m)

ϵ_0 : Vacuum permittivity (F/m)

k : Boltzmann constant (J/K)

T_e : Electron temperature (K)

n_e : Electron density (m^{-3})

e : Elementary charge (C)

Thus, N_D represents the particle density (density) on each side by density of the electron on the Debye surface and the temperature. In order for plasma life, $N_D \gg 1$ ^{29,30}

$$N_d = \frac{4\pi}{3} n_e \lambda_D^3 \quad (6)$$

2. Materials and Methods

Moringa plant specimens were taken from a herbarium and prepared according to a very strict process according to the needs of laser plasma-stimulated spectroscopy (LIBS) and optical emission spectroscopy methods (OES). The plant samples were dried and finely processed into a homogeneous powder, and 1.5 g of the powder was weighed with high precision. The powder was compressed into cohesive discs 20 mm in diameter and approximately 3 mm in thickness. using a hydraulic press at approximately 6 MPa for 10 min. Solid discs were prepared and used as solid targets for plasma generation, during which the characteristic atomic emission spectra of the *Moringa* components were recorded, analyzed, and measured using LIBS and OES techniques.

3. Results

3.1. Optical Emission Spectroscopy (OES) Analysis of *Moringa* Plasma.

Optical emission spectroscopy (OES) has been one of the major non-destructive diagnostic methods utilized in LIBS plasma studies. It provides elemental composition, atomic processes of excitation, and physical status of the plasma through analysis of the emission lines released from laser-generated plasma. In this respect, the optical emission spectra of a *Moringa* sample at optical wavelengths (300–900 nm) are shown in **Figure 1** at various laser energies (50, 150, 250, 350, and 450 mJ).

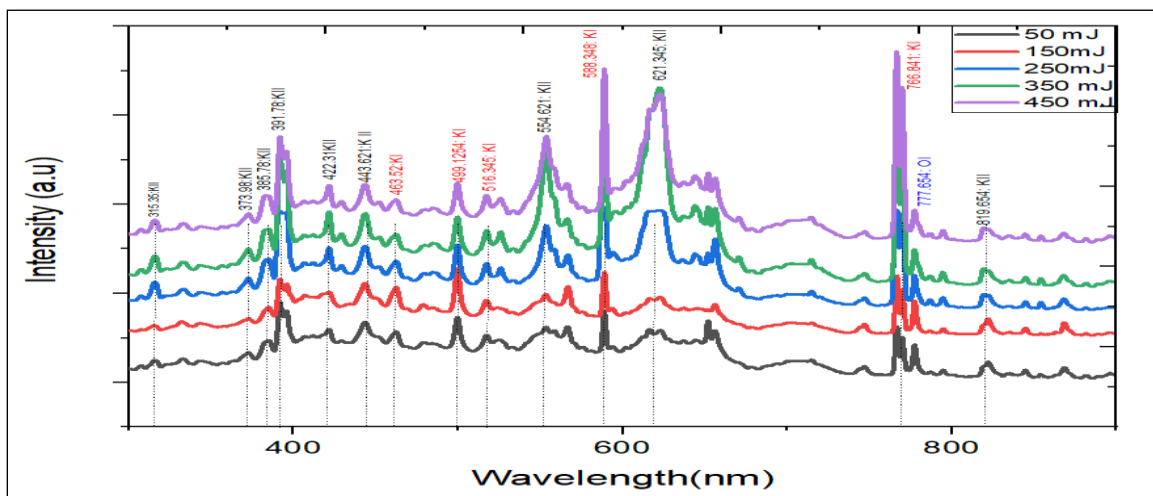


Figure 1. *Moringa* sample plasma optical emission spectra generated in the atmosphere with different laser power.

Boltzmann plots of *Moringa* spectra at various laser energies (50–450 mJ) at LIBS are presented in **Figure 2**. Each graph plots the performance of the resulting plasma at a given energy level and demonstrates the influence of laser energy on energy level distribution and electron temperature.

(a) Laser energy: 50 mJ. The plot shows acceptable linearity with relative scattering at spectral points, implying that at 50 mJ:

Relatively weak plasma formation. Such is the low excitability of the atoms. Electrons are heated at a lower temperature than high energies. This is due to the little material that is evaporated from the *Moringa* surface at a lower energy. But the visible linearity proves the initial LTE condition.

(b) Laser energy: 150 mJ. The linearity increases considerably at 150 mJ, and the points scattered around the straight line decrease:

Improved absorption efficiency of laser-amplified energy. More excited atoms in a material. Improved plasma stability. The slope of the line is lower than the 50 mJ values, reflecting a higher electron temperature, which agrees with the values we have computed with the plasma coefficient table.

(c) Laser energy 250 mJ. This chart illustrates the plasma changing to a stable state for the following:

The linearity is more pronounced. The points are more evenly distributed at or around the line. The random emission of spectral light is then reduced. This mirrors the state of near-ideal local thermal equilibrium (LTE) of the plasma, which makes this energy level extremely suitable for accurate spectral calculations.

(d) Laser energy 350 mJ. By 350 mJ the slope is drastically decreased and reflects the following: Significant rise in electron temperature. Improving collision ionization processes. High electron density in the plasma. An improved plasma stability is also made possible on this basis: the uniformity of all the spectral points indicates high stability of the plasma as well as its stability in high-scale spectral studies and thus makes the ideal energy for sophisticated spectral analysis.

(e) Laser energy: 450 mJ. This state is the most stable plasma, consisting of the following:

Low slope to straight (more Te). Low point dispersion. Most uniform distribution of energy levels. This indicates that the plasma is dense and stable, with an enormous improvement in excitation efficiency, which is without saturation and without spectral shift, confirming that this energy is in the best form for *Moringa* spectroscopy. General conclusion from all the figures:

The higher the laser power, the better the linearity of Boltzmann diagrams. Increase in the electron temperature. Stability of plasma at high energies. *Moringa* is used as a good sample for LIBS-based plasma diagnostics.

Table 1 displays the values taken from the Boltzmann plots of the emission spectra of the *Moringa* sample at various laser energies (50–450 mJ). The potassium emission lines at different wavelengths were used to calculate the slope of the curve, the correlation coefficient, the electron temperature (Te), and the absolute temperature (T).

1. Slope of the Curve and its Physical Significance

It can be observed from the table that the slope value is negative in all cases, as theoretically predicted. The slope gradually decreases (becomes less negative) from -0.7704 at 50 mJ to -0.7487 at 450 mJ. This decrease in slope directly indicates a rise in electron temperature with increasing laser energy, which is consistent with the trends shown in **Figure 2**.

2. Correlation Coefficient (R^2) and the Validity of Local Thermal Equilibrium (LTE). Boltzmann's results showed acceptable linearity, indicating consistency among the selected emission lines. However, this alone does not constitute evidence of local thermodynamic equilibrium. The R^2 values range between 0.78 and 0.81, which are good values in LIBS experiments for biological samples and indicate A clear linearity between $\ln(I\lambda/gA)$ and E_k . A satisfactory degree of fulfillment of the Local Thermal Equilibrium (LTE) condition. The reliability of using the Boltzmann method to calculate Te. A slight improvement in R^2 is also observed at higher energies (350–450 mJ), indicating improved plasma stability.

3. Electron Temperature Evolution (Te), The electron temperature gradually increases from 1.298 eV at 50 mJ to 1.352 eV at 450 mJ. This reflects, improved electron excitation efficiency, Increased laser energy absorption. Enhanced collision processes within the plasma, increasing the laser power leads to a decrease in the slope of the curve. An increase in Te improved plasma stability. The slope = $-1/(kT_e)$, a decrease in the absolute slope indicates an increase in electron temperature.

Table 1. shows the values extracted from the Boltzmann plots of the emission spectra of the *Moringa*

E mJ	slope	R2	Te (eV)	T (k)	Atom	Wavelength(nm)
50	-0.7704	0.7878	1.298	15056.8	K I	464.1876
150	-0.763	0.7851	1.30616	15203.14548	K I	496.5031
250	-0.762	0.7815	1.329787	15425.53191	K I	511.2249
350	-0.7539	0.8024	1.340483	15549.59786	K I	583.1887
450	-0.74874	0.8051	1.351534	15677.7943	K I	766.489913

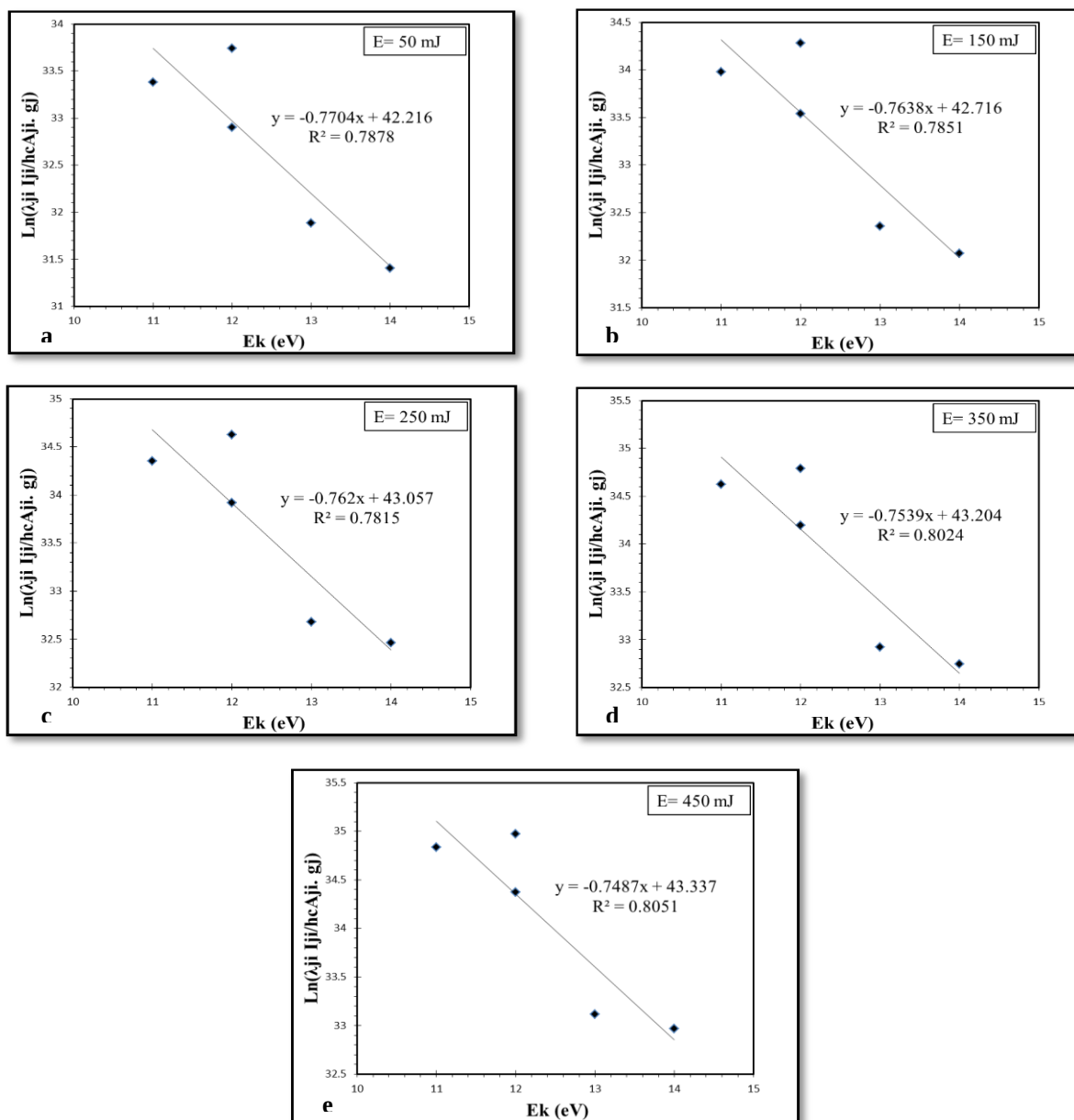


Figure 2. Effect of laser energy on the spectral properties of the *Moringa* herb using laser-induced breakdown spectroscopy (LIBS) at: a. laser energy =50mJ, b. laser energy =150mJ, c. laser energy =250mJ, d. laser energy =350mJ and e. laser energy =450mJ

3.2. *Moringa* spectral interpretation analysis spectra (Lorentz fitting).

Figure 3 shows the optical emission spectra of the *Moringa* sample in the spectral domain (496–504 nm) at five laser-induced energies (50, 150, 250, 350, and 450 mJ). Physically, the plasma generated was well characterized by the spectral peaks through Lorentz fitting. Emission Intensity at Higher Laser Energies. The figure shows that the spectral peak intensity in this case increases slowly at increasing laser energy 50 mJ to 450 mJ. This corresponds to the energy levels of the laser emitted by the sensor. This rise can be explained by the number of excited atoms and ions in the plasma increasing. Enhanced laser absorption property within the sample. Increased temperature and density of the plasma resulting from the plasma above the *Moringa*. This behavior indicates increased atomic excitation at high energies, implying stable plasma formation. The stability of the spectral peak location (approximately ~500 nm). The spectral peak position is nearly constant across all energies. The electron transitions responsible for the emission at 500 nm involve a single element, typically calcium (Ca), magnesium (Mg), or specific organic molecular lines, that we are focusing on. Absence of a large wavelength shift demonstrates chemical reactivity and the non-altering nature of the sample's chemical composition in the absence of structural transformation with a rising energy.

3.3. Lorentz Fit and Physical Meaning

The Lorentz fitting suggests that: The Stark broadening is the principal influence on the peak width (FWHM). The expansion of peak width as energy increases suggests higher electron density in the plasma. Increased collision of charged particles. The Lorentz spectral line width at half height (FWHM), used to calculate the Stark equation, was employed to estimate the electronic effects. It was observed that the FWHM value increased with increasing laser power, indicating an increase in electron integrals within the plasma. This facilitates the use of these peaks to compute electron density. Plasma temperature. Laser discharge stability. Significance of Results for *Moringa* Applications. The spectral results prove that *Moringa* exhibits a dynamic response to increasing laser intensity. The obtained plasma is steady and suitable for: Elemental analysis (LIBS). Plasma activation effects. Medical and biological uses (antibacterial activity, sterilization). Lorentz-fitted emission spectra of *Moringa* samples obtained under varying laser energy (50–450 mJ) are shown in **Figure 3**. We witness a distinct increase in emission intensity with laser irradiation in response to higher plasma temperature and electron density. The emission peak is maintained at ~500 nm at all energies, demonstrating stable transitions of the elements. Based upon the Lorentzian profile, Stark broadening appears to be the most preferred line-broadening mechanism due to plasma electron density at the higher laser energies.

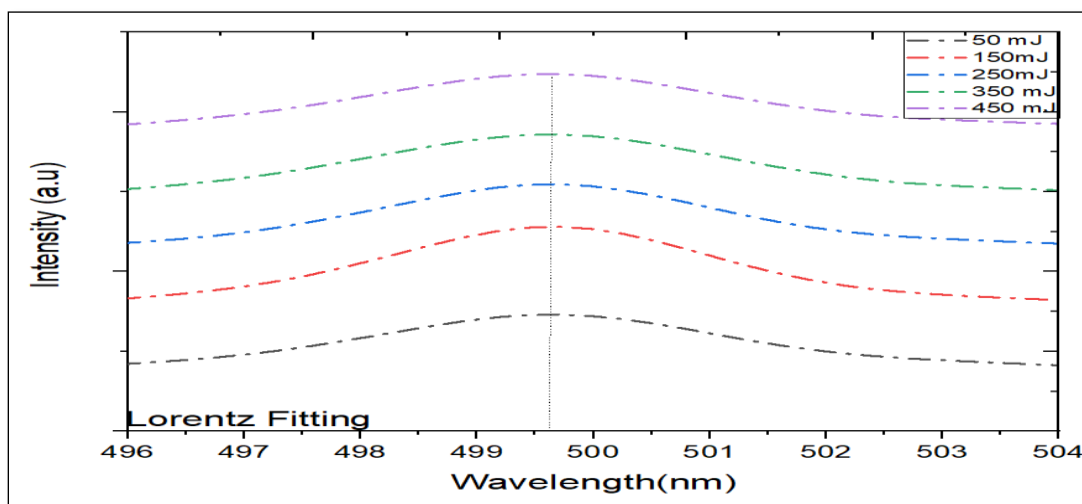


Figure 3. The *Moringa* target's striking distribution at different laser energy

Figure 4 shows the relationship between laser energy (mJ) and electron temperature (T_e) and electron density (n_e) of the plasma for *Moringa*, which was obtained by LIBS. The blue dots represent T_e values (left axis); red squares also represent n_e values (right axis). The increase in electron temperature (T_e) is stepwise, going from about 1.298 eV at 50 mJ to 1.352 eV at 450 mJ. This behavior reflects:

The sample is absorbing more of the laser energy. Promoted electron excitation in the plasma. Average electron energy is increased. The almost linear correlation between T_e and laser energy indicates the stability of the plasma at higher energies without reaching thermal saturation. Electron Density (n_e) Behavior. The electron density increases from about $6.15 \times 10^{17} \text{ cm}^{-3}$ to $9.75 \times 10^{17} \text{ cm}^{-3}$ with increasing laser power. This increase is due to: A higher rate of collision ionization. The amount of material vaporized from the surface of the *Moringa* increases. The development of a denser plasma with higher energies. The rate of increase on n_e seems to be relatively faster than on T_e , which means the excess energy is being invested for ionizations, not heating. Relationship between T_e and n_e . The figure indicates that both parameters increase synchronously with increasing laser power, suggesting, a strong coupling between excitation and ionization. Stability of plasma dynamics. Accomplishment of conditions for local thermodynamic equilibrium (LTE). This behavior corroborates the efficacy of Boltzmann plot and Stark broadening technique for analyzing *Moringa* spectra. General Physical Implications. The results show that increasing laser power causes improved laser interactivity with matter. More packed, hotter plasma. Better spectral signal quality. Thus, energies of 350–450 mJ are the optimal range for stable plasma for *Moringa* characterization.

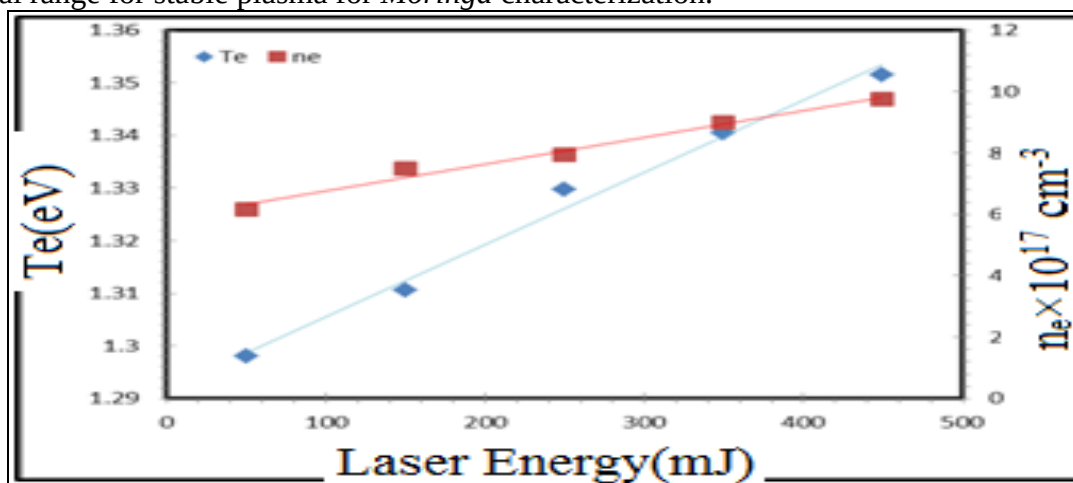


Figure4. Influence of Laser Energy on T_e and n_e *Moringa* Plasma.

Moringa sample in terms of laser energies from 50 to 450 mJ. These parameters shown in table (2) are electron temperature (T_e), electron density (n_e), plasma frequency (f_p), length of the Debye sphere (λ_D), number of particles (N_d) in the Debye space, and the modulus of the plasma (Λ).

1. Electron Temperature (T_e)

We see T_e increasing gradually from 1.298 eV at 50 mJ to 1.3515 eV at 450 mJ. This behavior demonstrates that as laser energy increases,

This is expected to increase the energy absorption in the plasma.

Increased excitation-ionization processes.

Higher average electron energy. This indicates a greater formation of energetic plasma at higher energy levels.

2. Electron Density (n_e)

The electron density increases from $6.15 \times 10^{17} \text{ cm}^{-3}$ to $9.75 \times 10^{17} \text{ cm}^{-3}$ with increasing energy.

This is due to:

Higher collision rate between photons and atoms due to stimulation of several ionization processes in *Moringa* elements (K, Ca, Mg).

These values indicate that a dense plasma has been obtained and prepared for quantum spectroscopy.

3. Plasma Frequency (fp)

fp rises from 7.04×10^{12} Hz to 8.87×10^{12} Hz, which corresponds exactly with an increase in electron density, increasing ne leads to increasing fp.

4. Debye Length (λ_D)

At the high energy level, a decrease in Debye length by slightly less as 0.259×10^{-5} cm to 0.240×10^{-5} cm reflects the following:

Higher charge build-up in the plasma

The plasma has a higher capacity to cover electric fields.

Collective behavior: More cohesive formation of plasma.

5. Number of particles in the Debye sphere (Nd)

Nd values decrease with increasing energy from 0.058×10^3 to 0.045×10^3 which can be explained by the fact that $ND \gg 1$ confirms collective plasma behavior.

Now, this decreases the size of the Debye sphere.

The plasma will have a denser and less diffuse state than the one from the past.

6. Plasma modulus (Λ): High values of Λ (ranging from 175 to 132) imply that

At All Energies, this plasma criterion $\Lambda \gg 1$ is thus obtainable. The studied system is a plasma, which is true and stable. Spectral analysis can be performed, and results are reliable for physical investigation. The conclusion is that the rising Te, ne, and fp compared to decreases in λ_D and Nd indicates that increasing the laser power changes the properties of *Moringa*-generated plasma. This configuration is extremely appropriate for LIBS/OES analyses and high-resolution phytochemical examinations that are consistent with the stability of the plasma system.

This confirms that *Moringa*-derived plasma is real plasma. All laser energies met with the plasma conditions.

The Spectra results are scientifically trustworthy.

Λ decreased with increasing laser energies:

(Λ) decreases since a smaller Debye length exists.

The reduction in the size of the Debye sphere occurs even though the electron density increases.

The plasma parameter (Λ), which indicates the number of charged particles in the Debye sphere, was significantly above unity for all laser energies, confirming the formation of a genuine and stable plasma that can be analyzed by spectroscopy.

Table 2. The *Moringa* plasma parameters

E mJ	T _e (eV)	n _e × 10 ¹⁷ cm ⁻³	f _p (Hz) * 10 ¹²	λ _D × 10 ⁻⁵ (cm)	N _d × 10 ³	Λ
50	1.298	6.15	7.042289826	0.259426442	0.058493258	175.4798
150	1.31061599	7.5	7.776908126	0.244418178	0.052291205	156.8736
250	1.329787234	7.95	8.006816971	0.242890729	0.048599972	145.7999
350	1.340482574	9	8.519176016	0.241393489	0.046418446	132.5036
450	1.351533991	9.75	8.867039529	0.24031041	0.044955851	134.8676

4. Discussion

4.1. General Effects of Laser Energy on Spectral Intensity.

Emission lines gradually grow in intensity with increasing laser power²⁹. The spectrum at 450 mJ (violet curve) shows the maximum intensity and most prominent peaks. This trend in the intensity of the emission lines reflects more mass that is ablated from the surface (ablation mass) plus an increase in plasma density and electron temperature. That in agreement is confirmed by the electron temperature and electron density obtained previously from the Boltzmann diagrams. Higher laser energy increased line intensity and FWHM due to stronger Stark broadening.

4.2. Spectral Line Detection and Element Identification.

An array of strong emission lines has been determined for several of the elements present in *Moringa*, with the highest value obtained from potassium (K1 and K2): 373.98 nm, 385.78 nm, 404.41 nm, 493.93 nm, 516.95 nm, 588.34 nm, and 766.84 nm. The most apparent lines are those of K1²⁹, which suggests significant sources of potassium in *Moringa* samples, a key nutrient present in medicinal plants. Calcium (Ca²⁺): 393.37 nm, 396.85 nm. The formation of Ca²⁺ lines signifies something. High excitation energy. A plasma temperature suitable for partial ionization. Sodium (Na I): 589.12 nm. This is a common and characteristic line in biological samples, and its intensity increases with increasing laser intensity. Oxygen (O I): 777.65 nm³⁰. It is the presence of this line that reveals the following: Organic materials in the sample. The surrounding atmosphere is important for generating the plasma. Laser power is influencing spectral line widening. With increasing laser power, the lines are sharper and more distinct. The spectral widening is enhanced. This is attributed to increased Stark broadening; plasma is denser, containing high electron density. This corroborates the electron density results from the plasma. Stability of Plasma and Homogeneity. The uniform appearance of the same lines at all energies suggests a stable elemental composition. Notice the absence of unexpected lines, indicating the sample is uncontaminated. Plasma of excellent homogeneity.

Correlation in relation to physical plasma analysis. The OES indicates that the electron temperature (Te) is higher than before, indicating an enhancement in temperature. Higher electron density (ne). Better local thermal equilibrium (LTE) conditions. A stronger emission line intensity shows that there are more excitation and ionization processes happening because of the increased laser power.

5. Conclusion

In this research, it was shown that LIBS (laser-induced breakdown spectroscopy), underpinned by optical emission spectroscopy, is a well-controlled and non-destructive diagnostic technique for elemental composition and plasma parameters of *Moringa oleifera*. More extensive utilization of the laser was characterized by spectral line intensification enhancement, gradual increase in temperature and electron density, and reduced Debye length and plasma parameters. This indicates a higher density and stability of plasma at high energies, particularly around the 350–450 mJ values. High plasma parameter values ($ND \gg 1$) that satisfy the Debye criterion indicate a real plasma context and the fulfillment of local thermal equilibrium requirements, thereby increasing the robustness of the results. In addition, the Lorentzian fitting indicated that Stark amplitude is the main factor in Stark broadening and showed a majority of charged particle exchange in the plasma. Thus, *Moringa* could be a suitable plant model for studying spectroscopy and plasma with the possibility to be applied for advanced plant analysis, biomedicine, and plasma-based processes in green technological fields.

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Conflict of Interest

The authors declare that they have no conflicts of interest.

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Ethical Clearance

The procedures followed are consistent with ethical standards. The guidelines of the educational institution for research were followed.

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