Investigating the Relationship between Zinc Deficiency and Renal Failure using Laser-Induced breakdown Spectroscopy (LIBS)

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ABSTRAC: Kidney failure is a common health problem affecting millions of people worldwide, and zinc deficiency is a major contributor to this condition. In this study, the use of a laser-induced breakdown spectroscopy (LIBS) technique for the diagnosis of renal failure in zinc-deficient individuals was validated. The study was conducted by analyzing plasma samples collected from individuals with renal failure and zinc deficiency using the LIBS technique. Then the plasma parameters, such as electronic temperature and electron density, were analyzed and their equations were derived. To identify the characteristic spectral lines of elements in blood samples and compare them with those of healthy individuals. The results showed that the plasma parameters of individuals with renal failure and zinc deficiency were significantly different from those of healthy individuals. This study demonstrates the potential of the LIBS technique as a non-invasive diagnostic tool for renal failure in zinc-deficient individuals.

Keywords: plasma, blood minerals, Renal failure , LIBS, zinc deficiency, early diagnosis, diagnostic tool.

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1. Introduction

Kidney failure is a common health problem that affects millions of people worldwide. This condition occurs when the kidney is unable to effectively remove waste and excess fluid from the body [1]. Zinc, an essential trace element, plays a critical role in many biological processes, including immune function, wound healing, and DNA synthesis [2]. Zinc deficiency has been identified as a significant contributor to renal failure. Traditional methods of diagnosing kidney failure include blood and urine tests, which can be time-consuming and unreliable [3]. Therefore, a rapid and accurate diagnostic tool specifically designed to identify renal failure in zinc-deficient individuals is needed. Laser-induced breakdown spectroscopy (LIBS) is an advanced analytical technique that has received a lot of attention in recent years [4]. This method of spectroscopy involves using a high-energy laser to vaporize a small portion of a sample, which results in a plasma that emits distinct wavelengths of light. By analyzing the resulting spectrum, researchers can determine the elemental composition of a sample. Emerging evidence indicates a possible link between zinc and the development of renal failure [5]. Some studies have shown that zinc supplementation can enhance kidney function in animal models of kidney disease [6]. However, the exact mechanisms underlying this effect are not yet fully understood. The LIBS application provides an opportunity to investigate the effect of zinc on renal failure by analyzing zinc levels in kidney tissue or blood samples obtained from patients with this condition [7]. By using LIBS to assess zinc levels and their relationship to kidney failure, researchers can advance our understanding of zinc's role in kidney health. This may lead to the development of targeted interventions, such as zinc supplementation, for individuals at risk of renal failure or who already have renal failure. [8]. The aim of this research is the importance of zinc in detecting kidney failure [9]. It highlights the need for a rapid and accurate diagnostic tool that specifically identifies kidney failure in individuals with zinc deficiency. Laser-induced breakdown spectroscopy (LIBS) as an advanced analytical technique can be used to evaluate zinc levels and investigate the relationship between zinc and kidney failure. [10]. The goal is to advance our understanding of the role of zinc in kidney health and perhaps develop targeted interventions, such as zinc supplementation, for individuals at risk of kidney failure or who already have kidney failure [11].

2. PLASMA PARAMETERS

A plasma is composed of atoms, molecules, ions, and electrons and can be considered electrically neutral on a statistical level. The degree of ionization determines whether a plasma is partially or completely ionized. Partially ionized plasmas contain neutral atoms, while completely ionized plasmas do not [15]. When describing the type of plasma generated, it is important to determine whether the plasma is in thermodynamic equilibrium (TE), which requires knowledge of the electron density and electron temperature [16]. In two cases, their electron temperature can be determined through the measurement of intensity ratios. The first case involves comparing the intensity ratios of ions to neutral lines and neutral to neutral lines, which are spectral lines originating from different upper levels of the same element and ionization stage. In the second case, the Boltzmann equation is utilized to construct a Boltzmann plot [17]. In the first case, the line intensity is combined with the Boltzmann equation to determine the excitation electron temperature. The relationship between them can be expressed as

$$T_e = \frac{-(\mathrm{E}_1-\mathrm{E}_2)}{\mathrm{k}\ln\left(\frac{\mathrm{I}_1\lambda_1\mathrm{A}_2\mathrm{g}_2}{\mathrm{I}_2\lambda_2\mathrm{A}_1\mathrm{g}_1}\right)}$$
(1)

The spectroscopic constants (I, l, g, A, K, and E) represent the line intensity, wavelength, statistical weight, transition probability, the Boltzmann constant, and the energy of the excited state, respectively. In the second case, which utilizes the Boltzmann equation to generate the Boltzmann plot, it is considered another method used to find the electron temperature. The intensity (I) of a spectral line corresponding to the transition between the levels Ek and Ei of atomic species can be given by the below equation [18].Therefore, the aim of the introduction is to highlight the importance of zinc deficiency in renal failure, the potential of LIBS as a diagnostic tool, and the need for further research to understand the relationship between zinc and kidney health.

$$I = \frac{hc}{4\pi\lambda} \, . N(T) \frac{A_{Ki} g_k}{U(T)} \exp\left(-\frac{E_k}{KT_e}\right) \qquad (2)$$

where h, c, λ, N(T), A_{ki}, g_k, E_k, T_e, K, and U(T) represent the blank The emitted spectral line intensity from a specific excitation state provides information for evaluating the electron temperature. To accurately assess the wavelengths (λ), transition probabilities (Aki), and intensities (I) of the lines, they must be well resolved. By taking the natural logarithm of both sides of equation (2), it can be expressed as [19]:

$$\ln\left(\frac{I\lambda}{A_{ki} g_k}\right) = -\frac{E_k}{KT_e} + ln\left(\frac{hcN}{4\pi U}\right) \qquad \textbf{(3a)}$$

In the above-mentioned Saha Boltzmann equation, for the specific species, the final term is constant. The equation (3 a) becomes

$$\ln\left(\frac{I\lambda}{A_{ki} g_k}\right) = -\frac{E_k}{KT_e} \qquad \textbf{(3b)}$$

So, plotting left-hand side of Eqn. (3b)Vs. E_k for the spectral emission line number will give a direct line of slope $(-\frac{1}{K\,T_e})$ and intercept ln (hcN/4πU). Thus, by measuring the slope, we can identify the temperature of the plasma. Also, one can measure the electron temperature in one emission spectral, as shown in the equation below [20, 21].

$$T_e = \frac{E_k}{K \ \ln\left(\frac{I\lambda}{A_{ki} g_k}\right)} \qquad (4)$$

The density of electrons (ne) refers to the number of free electrons per unit volume [22]. The plasma electron density indicates the number of ions or electrons that will interact with the laser and the resulting effects on the characteristics of each energy source. The electron density plays a crucial role in determining the thermodynamic equilibrium state of the plasma. Another important consideration is whether the density of electrons is sufficiently high for collisions to dominate the population of energy levels. This criterion, known as the McWhirter criterion, was formulated to determine the critical electron density required to achieve the local thermal equilibrium (LTE) condition [23, 24].

$$n_e \geq 1.6 * 10^{12} . T_e^{1/2} . (\Delta E)^3 \qquad \textbf{(5)}$$

In the McWhirter criterion, the energy difference (ΔE) represents the gap between the lower and upper energy states in the transition lines of adjacent levels, measured in electron volts (eV). The electron temperature (Te) is expressed in Kelvin (K°). It is important to note that the McWhirter criterion serves as a necessary, though insufficient, condition for achieving local thermal equilibrium (LTE) and is usually satisfied during the initial stages of the plasma's lifetime [25].

3.Materials and Methods

3.1. Preparation of experimental samples

The Medical City Hospital in Baghdad, Iraq, provided blood plasma samples of patients with renal failure with various levels of urea and creatinine. We obtained a blood sample from an infected individual and another blood sample from a healthy individual , as shown in Figure 1. The plasma is formed at a frequency of 1 Hz, which means that it is formed in a single shot to avoid causing damage or delamination of the surface of the material. We collected the plasma spectrum of the fiber, passed it through the optical fiber, and then the data in the form of intensity as a function of wavelength was added.

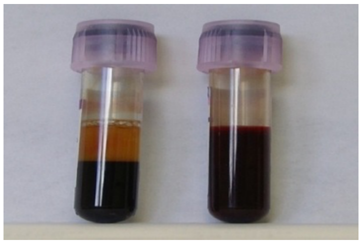

Figure 1: Two tubes of EDTA anticoagulant. Left tube: after sedimentation of blood components (plasma). Right tube: freshly collected blood.

3.2. LIBS system

In order to record the optical emission spectra of plasma ablation from the surfaces of medical samples for people with chronic renal failure, the following parts were used in the experiment: A Q-switching Nd-YAG laser was utilized with the following parameters: pulse duration of 10 ns, pulse repetition frequency of 1 Hz, wavelength of 1064 nm, and energy output of 100 mJ. The laser beam was focused on the sample's surface using a converging lens with a focal length of 10 cm. The beam was directed at an angle of 45° with a distance of 10 cm from the plasma, vaporization, and ionization produced by the sample. To capture the spectral information of the laser-target plasma, a fiber optic cable was employed to connect the plasma emission spectrum to a spectrum analyzer. The spectrum analyzer was connected to a charge-coupled device (CCD) equipped with an array of detectors, which recorded the spectral lines. For the data acquisition process, Thorlabs' PC program and a spectrum analyzer (CCS 100/M) were utilized. The resolution of the spectrum analyzer was 0.5 nm, and the time integration for recording the spectrum was set to 800 s. The recorded spectrum covered the wavelength range of 321-740 nm. The spectrum data was obtained from NIST [26]. Figure 2 illustrates the experimental LIBS system used for recording the optical emission spectra from the plasma ablation of medical samples taken from patients with chronic renal failure.

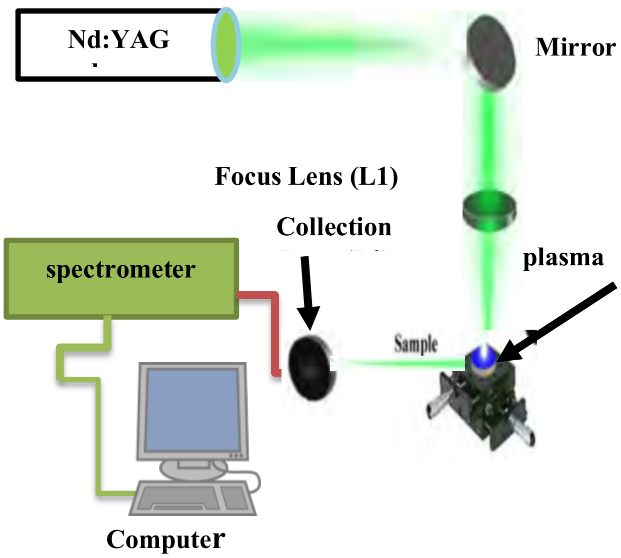

Figure 2: Schematic diagram of the experimental setup for LIBS.

Results and Discussion

The blood plasma components of samples, consisting of several metals, including zinc (Zn), were stimulated by a Q-switched negative Nd:YAG laser with (1064 nm), a laser pulse energy of 100 mJ, and a pulse duration of (10) ns. The collected plasma emissions are sent by optical fiber to the inlet slit of the spectrophotometer, which responds to a wavelength between 321 and 740) nm. The resulting spectrum distribution is plotted as intensity (I) versus wavelength (λ). The resulted spectral emission lines are (647.5847nm, 458.7827nm, 623.6961 nm, and 694.3199 nm, for Zn I), as shown in figures (3,4, 5).

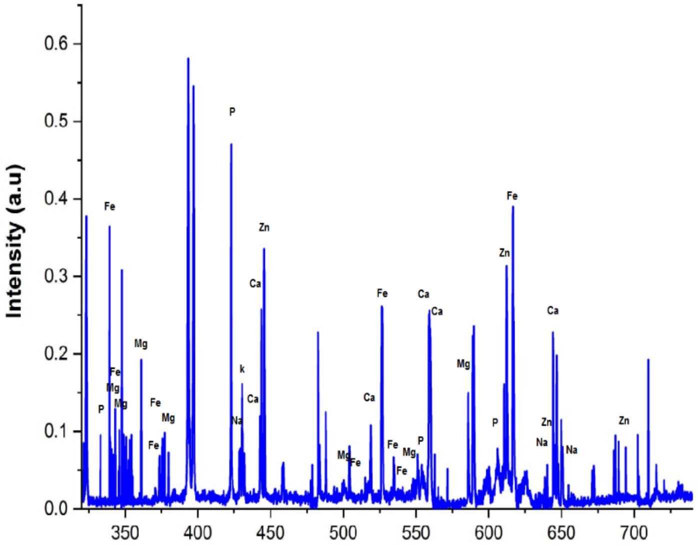

Fig. (3). The emission spectrum of sample (1).

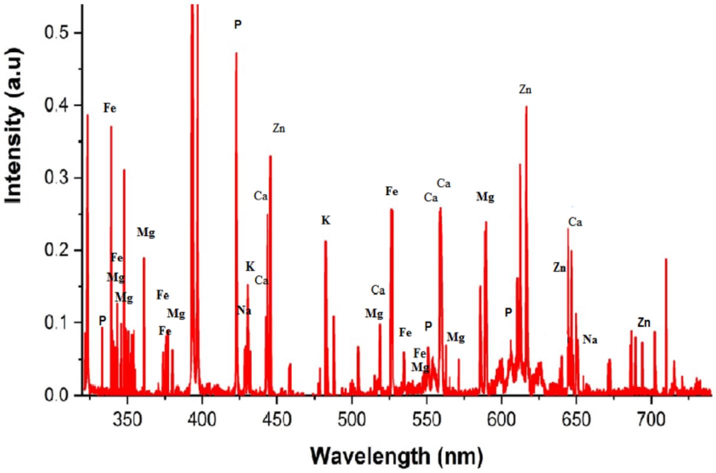

Figure (4): The emission spectrum of the sample (2).

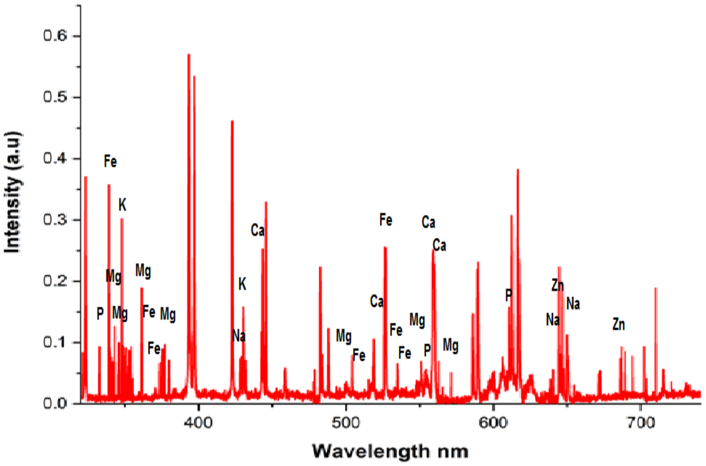

Figure (5): The emission spectrum of sample (3).

The samples' spectral lines are extremely important for obtaining important data required for determining atomic constants. The plasma temperature and electron density can then be calculated using these constants and the distinctive Fe lines. Tables 1-3 provide a list of the atomic and spectroscopic parameters of the neutral Zn Lines that are pertinent to this study. Investigating the presence and behavior of zinc traces in the serum of people from various groups can be supported by an analysis of these figures and the related tables. Researchers can learn more about the atomic characteristics of the existing zinc species by analyzing the emitted spectra, which in turn can help them gain a better understanding of the underlying physiological or pathological processes. The zinc traces in the affected people's serum are shown as emitting spectra in Figure 3.

These patients probably have particular illnesses or conditions that affect how their bodies use iron. The spectral lines emitted by the zinc species are indicated by the precise wavelengths depicted in this figure 3, which enable the calculation of atomic constants. The emission spectra from zinc traces in healthy people's serum are shown in Figure 5. This group, which represents individuals with typical zinc metabolism and excellent general health, acts as a control or baseline. Any notable variations in the emission patterns can be identified by people's serum. The word "impacted" implies that these people's zinc metabolism has been changed by some outside action or circumstance. The spectra shown in this figure provide a way to examine and comprehend how such factors affect the emission characteristics of zinc species. Researchers can consult Tables 1, 2, and 3, which provide the atomic spectroscopic parameters of the neutral Zn lines, to further explain the results. The wavelengths, energy levels, transition probabilities, and other pertinent atomic constants related to the discovered Zn lines are presumably presented in these tables, along with other significant information. These variables are necessary for precisely computing the plasma temperature and electron densities, allowing for a thorough investigation of the zinc emission spectra. In conclusion, a scientific framework for analyzing the emitted spectra from zinc traces in the serum of afflicted, healthy, and unaffected individuals is described in the figures and tables. These results support calculations of atomic constants, comprehension of the atomic characteristics of the current iron species, and determination of plasma temperature and electron densities. Such information advances our understanding of zinc metabolism and its possible effects on health and disease. In contrasting the spectra in Figures 4 and 5, which may offer insights into the consequences of particular medical disorders. Figure 5 displays the emission spectra from zinc traces in affected. Table 4 shows the plasma parameters for the same spectral line of three different samples that were found using Equations (4) and (5).

Table 1: Spectral parameters of the spectral lines of elemental zinc for sample (1)**.**

Eu(cm^{-1}**)**	**El(** cm^{-1}**)**	**gkUp.**	**Aki(s^{-1})**	**I(a.u)**	**λ(nm) LIBS**
71 218.994	55 789.216	3	4.7e+07	0.05733	647.5847
68 070.882	53 672.239	1	4.7e+07	0.0777	694.3199
62772.014	46 745.403	5	2.4e+07	0.03941	623.6961
73 060.66	46745.4032	1	4.5e+06	0.071	379.979

Table 2: Spectral parameters of the spectral lines of elemental zinc for the sample (2).

Eu(cm^{-1}**)**	**El(** cm^{-1}**)**	**gkUp.**	**Aki(s^{-1})**	**I(a.u)**	**λ(nm) LIBS**
68 070.882	53 672.239	1	4.7e+07	0.07925	694.3199
62772.014	46 745.403	5	2.4e+07	0.0402	623.6961
73 060.66	46745.4032	1	4.5e+06	0.5934	379.979
75 628.35	53672.239	3	1.56e+07	0.05848	458.782

Table 3: Spectral parameters of the spectral lines of elemental zinc for the sample (3).

Eu(cm^{-1}**)**	**El(** cm^{-1}**)**	**gkUp.**	**Aki(s^{-1})**	**I(a.u)**	**λ(nm) LIBS**
71 218.994	55 789.216	3	4.7e+07	0.05848	647.5847
68 070.882	53 672.239	1	4.7e+07	0.07925	694.3199
62772.014	46 745.403	5	2.4e+07	0.0402	623.6961
73 060.66	46745.4032	1	4.5e+06	0.5934	379.979

Table (4): Plasma parameters for the same spectral line in different samples.

Sample No.	**T_e (K)**	**N_e (cm^{-3})**
Sample 1	6959.662	8.92329E+14
Sample 2	7217.83	8.84788E+14
Sample 3	6825.077	8.95844E+14

These parameters tell us important things about the thermal and electrical properties of the plasma. With an average electron temperature (Te) of 6959.662 K and an average electron density (Ne) of 8.92329 E^{+14} cm^3, sample 1 (healthy individual) displays the fundamental properties of normal plasma. The Te slightly rises to 7217.83K in sample 2 (patient individual), indicating a higher thermal energy than in sample 1 (healthy individual). Additionally, the Ne rises to 8.84788E^{+14} cm^3, indicating a larger concentration of free electrons, perhaps as a result of the addition of more charged particles to the plasma.

In contrast, Sample 3 (the damaged sample) exhibited a somewhat lower Te of 6825.077 K than the unaffected sample. Since the Ne in this sample is 8.95844E^{+14} cm^3, there are probably fewer free electrons present. These changes in Te and Ne can be a result of factors affecting the sample, such as illness or other environmental circumstances. Te is the average kinetic energy of the electrons in the plasma, and it gives information on the sample's thermal state. Ne, on the other hand, reflects the concentration or density of free electrons per unit volume and is essential for comprehending the electrical behavior of the plasma. Researchers can gauge changes in plasma conditions by comparing the plasma parameters between the various samples and detecting differences in thermal energy and electron density. These discoveries are crucial for understanding plasma physics, diagnosing problems, and using plasma technology in a variety of disciplines like material science, astronomy, and fusion research. The comprehension of the physical and chemical processes taking place inside the samples is made easier by understanding the plasma properties. This knowledge can aid in the development of diagnostic methods and treatment plans for disorders affecting the impacted sample, as well as developments in plasma-based technology. Overall, the plasma parameters shown in Table 4 provide helpful information about the features and behavior of the plasma in various samples, opening up possibilities for further study and applications.

4.Conclusion

This study confirms zinc's importance in kidney function and other biological functions. Zinc deficiency may cause renal failure. Laser-Induced Breakdown Spectroscopy (LIBS) quickly and reliably measured zinc levels in kidney tissues and blood. Emitted spectra revealed elemental composition and zinc's renal health effects.
LIBS can examine zinc deficiency and kidney failure. Zinc deficiency might help diagnose kidney failure and monitor renal illnesses early.

This method clarifies how zinc supports renal function. This could lead to targeted treatments like zinc supplements for kidney failure patients and at-risk patients. In conclusion, LIBS may help us comprehend zinc's involvement in kidney health and develop customized methods for preventing and treating renal failure.

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