

Rapidly growing trends in laser-induced breakdown spectroscopy for food analysis

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ABSTRACT

Laser-induced breakdown spectroscopy (LIBS) is a simple, rapid, and sensitive analytical technique that has been employed in a number of scientific disciplines (e.g., chemistry, physics, geology, engineering, material science, polymer science, environmental science, and metallurgy) for almost two decades. LIBS became vastly popular in industry, especially in steel, automobile, and aircraft manufacturing due to the availability of portable instruments and rapid analysis. As the technique can be employed for simultaneously analyzing both light and heavy elements, LIBS has attracted global attention for its food analysis capabilities to characterize micronutrients, essential constituents, and toxicants present in food items. No other technique provides such comprehensive analytical data in a short period of time without any substantial sample treatment. This paper reviews applications of LIBS for food analysis in recent years and discusses its potential to advance the characterization of components in food.

Keywords: Laser-induced breakdown spectroscopy ; food adulteration ; food classification ; spectroscopic techniques

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Introduction

Food is one of the basic requirements of life on this planet and humans need to remain vigilant when making food choices in their diet. Whether grains, fruit, vegetables, meat, or dairy products, it is important to know the constituents present in the food that we consume, which is why food analysis is crucial in an increasingly globalized food industry. Two general categories of constituents are determined in different foods: (1) essential components and (2) toxicants. Essential components may be further divided into subcategories of fats, proteins, minerals, and micronutrients. Toxicants include heavy metals such as cadmium, lead, and mercury, as well as organic toxicants that are typically present in liquid form.

In the last 150 years, more sensitive analytical techniques (e.g., spectroscopic, chromatographic, electroanalytical, biological, and radioanalytical) have emerged in the field of analytical chemistry that are now being successfully employed for food analysis. Food adulteration, the addition of harmful and sometimes hazardous material in edible foods, is a common practice found in various parts of the world. For example, the use of toxic organic dyes in sweets and ketchup, or urea and formaldehyde added to milk, frequently occur in underdeveloped countries. Hence, strict food analysis becomes a duty of the state to stop food adulteration and protect its citizens.

Atomic and molecular spectroscopic techniques have been employed to monitor different types of foodstuff and detect adulteration. Molecular fluorescence has been utilized to identify adulteration of olive oil^[1] and to characterize the type and freshness of oils.^[2] Similarly, the use of a near-infrared fluorescence-based chromogenic reaction made it possible to detect sulfites in food with a reasonably low detection limit of 31.6 nM.^[3] Furthermore, electrothermal atomic absorption spectroscopy has been used to determine heavy metal contamination in water samples.^[4,5]

Like other spectroscopic techniques, laser-induced breakdown spectroscopy (LIBS) has been extensively employed for food analysis. LIBS is advantageous in terms of ease of sample preparation and analysis speed, being employed to determine different elements present in fresh vegetables^[6] and for the analysis of food powders.^[7] Compared to other techniques, LIBS is a faster, more accurate, and more cost-effective analytical method, resulting in adequate precision without requiring lengthy sample preparation, making LIBS a desirable technique for the analysis of both fresh and processed foodstuff.^[8] Many efforts to optimize different LIBS parameters were identified for food analysis between 2009 and 2013. Attention was focused on the analysis of different plant varieties under various conditions to use LIBS. For example, elemental and ionic species of K, Ca, Mg, and other elements were determined in different varieties of wheat.^[9,10]

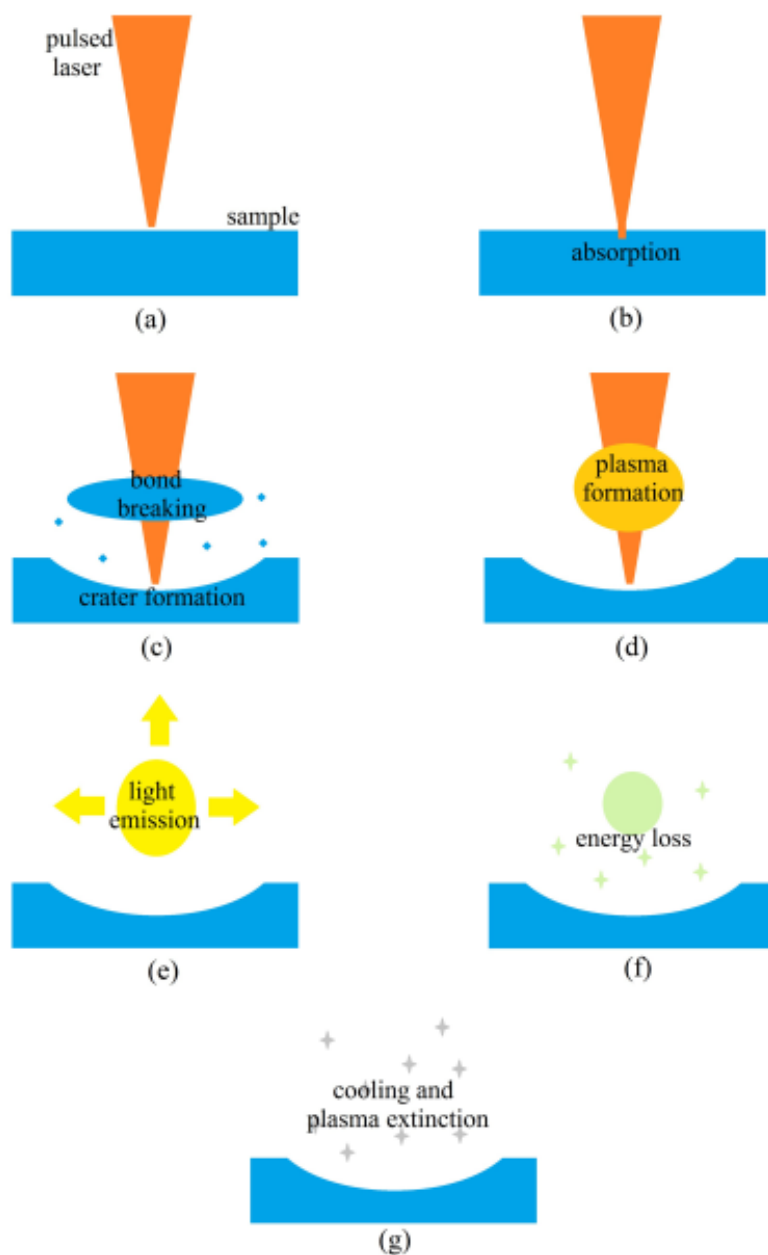
LIBS is a powerful analytical method to identify diverse components found in a variety of food. The nutrients and contaminants present in potato, spinach, and rice samples were identified by Kim and coworkers using LIBS.^[11,12] Common plant species in Asia were analyzed using LIBS to determine the antioxidants, glycemic elements, and contaminants present.^[13–17] Researchers have also employed LIBS to determine the amount of calcium present in different types of milk samples and fortified foodstuff for infants and young children (e.g., maternal milk, commercial infant formulas, and breakfast cereals) that is of significant importance globally.^[18,19]

In addition to direct food analysis, LIBS has also been employed successfully in the biotechnology sector to assess food-related diseases, such as to determine glycemic elements for diabetes management^[20] and identify biological contaminants (e.g., *Salmonella enterica*)^[21,22], and the analysis of algal biomass in industrial biotechnology.^[23] In recent years, the use of LIBS has increased and its optimization has tackled new challenges related to food analysis.

LIBS for direct food analysis

LIBS is based on the use of a laser pulse, which is focused on the sample to produce high temperature plasma. The sample breaks down due to this intense laser pulse through vaporization, atomization, excitation, and de-excitation within the plasma. The characteristic radiation, which occurs because of excitation of atoms in the sample, is captured and processed to characterize the components present. Although the plasma contains atomic, molecular, and ionic species from the sample, only characteristic atomic lines are registered by the monochromator. A solid-state Nd:YAG laser with nanosecond laser pulse duration is commonly used in LIBS.^[24,25] The formation of plasma that is obtained by focusing intense laser pulse radiation on a sample until it produces a dielectric breakdown is illustrated in [Figure 1](#).

Figure 1. Evolution of the plasma: (a) the laser is fired on the sample, (b) the species enter an absorption phase and (c) break their bonds, (d) the plasma is formed (e) that emits its radiation at different wavelengths, (f) then loses energy (g) until it becomes extinct.



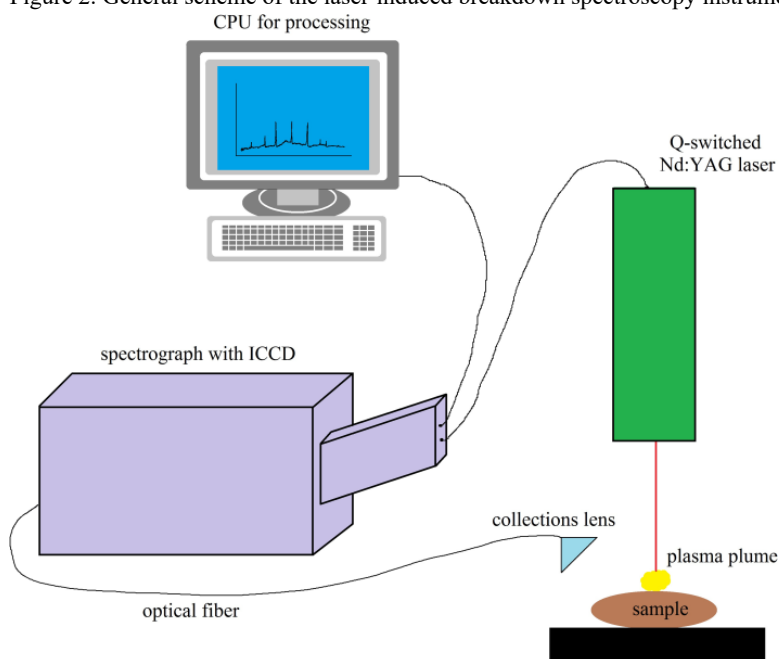
This rupture of the sample can be explained as the generation of a partially ionized gas after the action of a laser pulse, which is known as plasma.^[26] Thus when a laser pulse strikes a part of the sample, some radiation is lost through reflection or conduction, but most of the energy is absorbed and used to heat and overcome the latent heat of fusion and vaporization, finally resulting in atomization and molecule formation. These atomic and molecular species in the vapor state interact with the laser radiation reaching an excited or ionized state. Upon returning to the ground state, these excited species emit characteristic radiation that can be used to obtain an emission spectrum for qualitative and quantitative analysis.

Generated plasma can reach a temperature of 5000 to 20000 K. This plasma prevents the laser energy from effectively reaching the surface by means of a shielding effect, which gives rise to very energetic plasma, in which emission lines of greater intensity are produced than when this shielding does not occur. After one laser pulse, the system rapidly loses energy, which forms many excited atoms. The emitted light is captured by an optical fiber, which facili-

tates the detection of radiation. Finally, the plasma loses energy until it disappears and only the suspended particles remain in focus.^[27]

A schematic diagram of a LIBS apparatus commonly used for food analysis is shown in Figure 2. The laser irradiation from a Nd:YAG laser can be directed on the sample through a combination of mirrors and prisms, and then focused through the use of lenses. An important aspect when working with LIBS is to define the focal length, the location of the sample, and the position of the optical fiber that will be responsible for transporting the plasma to the detection system. The optical fiber is accompanied by a collimator that is used to homogenize the trajectories of the plasma emitted at the source.^[28]

Figure 2. General scheme of the laser-induced breakdown spectroscopy instrumentation.



Commonly used detection systems for LIBS consist of the Czerny-Turner or Echelle type spectrographs. Either a charge-coupled device (CCD) or intensified charge-coupled device (ICCD) can be used to detect emitted lines, the latter of which provides greater resolution and better sensitivity. Emission spectral data are typically analyzed with specialty software that varies from manufacturer to manufacturer.^[29]

LIBS can be used for qualitative as well as quantitative analysis of food items by analyzing the emission spectra obtained by direct food analysis. For qualitative analysis, hyperspectral imaging of LIBS spectra obtained from either the surface or interior of the food sample can be assessed. Hyperspectral images can be used to prepare principal component analysis (PCA) score maps that are useful for identifying and locating metals and other inorganic species in the food composition, whether they are macronutrients or toxic elements. For example, Gamela et al.^[30] used 810 LIBS emission spectra and hyperspectral images to construct PCA score maps of red lentils, pea seeds, and pumpkin seeds to identify Ca, Mg, Na, K, and P macronutrients present.

For quantitative analysis, food samples should be minimally altered; appropriate grinding to reduce particle size (provide homogeneity) and subsequent grazing of that sample is ideal. By utilizing solid calibration standards and a calibration strategy that overcomes matrix effects, solid samples can be directly analyzed, making it possible to accurately determine micronutrients and toxic elements with high precision in the food samples.^[31]

Common foods analyzed with LIBS

The number of publications in which LIBS has been reported for food analysis has grown considerably in recent years.^[32] Whereas publication growth for other applications of LIBS has remained fairly stagnant, the number of publications related to food analysis has increased due to investigations.

Instrumental parameters, such as delay and exposure time, vary from food to food, and even among foods in the same food group. Analytical conditions must be optimized for each type of food because any change in the analytical parameters may change the analysis results. A summary of analytical conditions is listed in Table 1. The use of LIBS for the recent analysis of particular foods is discussed in greater detail below.

Table 1. Most common instrumental conditions in food analysis using laser-induced breakdown spectroscopy.

Food samples	Analysis type (qualitative or quantitative)	Analytes	Delay Time (μ s)	Exposure (μ s)	Energy pulse laser (mJ)	Reference
Milk and derivates	Quantitative	Ca	0.65	2	68.1	[40]
	Quantitative	NaCa	1.27	1010	150	[42]
Meat	Quantitative	Ca	3	1050	230	[56]
	Quantitative	NaK	1.27	1100	150	[51]
Vegetables	Qualitative	–	0.65	1050	36	[57]
	Qualitative	–	1.5	10	60	[59]
Wheat flour and others	QuantitativeQualitative	KMg	1.27	1100	150	[31]
	Quantitative	Ca	0.3	1050	50	[72]
Tea	Quantitative	Pb	1.5	2	30	[79]
	Qualitative	–	1.5	1050	100	[75]
Fish and seafood	Quantitative	CNC ₂	3	2	50	[83]
	Quantitative	CaKMgNaPS-FeZn	1	1050	40	[86]
Rice	Qualitative	–	1.5	3	40	[87]
	Quantitative	CdPb	1	3	60	[92]
Coffee	Semi-quantitative	FeCaKMgNa	1.28	1100	35	[95]
	Qualitative	–	11	2100	50	[94]
Edible salt	Quantitative	Na	1.27	1100	150	[102]
	Quantitative	Li	0.65	1050	20	[101]
Sugarcane	Semi-quantitative	CaMg	0.5	1050	80	[103]
	Qualitative	–	0.5	1050	80	[104]
Water	Quantitative	Sr	0.5	2	8	[106]
	Quantitative	Cr	0.25	1050	20	[107]

Milk and milk derivatives

LIBS enables the direct analysis of solid, liquid, and gaseous samples. One of the most common ways to analyze liquid milk samples is to place 0.5 mL of milk on high-quality ashless filter paper and then leave it for ~15 min in a clean atmosphere so that it partially dries and expands homogeneously. The lines of major minerals (Ca, Na, K, and Mg) and molecular bands of CN and C₂ can thus be observed to determine concentrations of different elements and to compare with the optimum levels of liquid milk samples.^[33–36]

Another method to analyze milk using LIBS is to lyophilize the milk and press it into a pellet using $\sim 10 \text{ ton}\cdot\text{cm}^{-2}$ pressure.^[37,38] An interesting methodology based on formation of a gel from milk samples using gelatin was introduced by Sezer et al.^[39] for LIBS analysis. Another attractive technique for milk analysis involves converting sprayed milk samples to aerosols by compression in a sprayer with air and argon. In this study, the signal-to-noise ratio of Ca was optimized using a flow rate of 1.64 mL/min and a delay time of 0.65 μs .^[40] These analyses are generally performed to first determine the constituents in milk and then to establish a standard method for detecting any milk adulteration. To this end, LIBS has been successfully employed for the analysis of Ca, Mg, K, and Na as macronutrients in solid samples of milk, infant formula, and food supplements. Although novel methods have been developed^[39,40], the most common technique is the preparation of solid samples as pellets.^[37,38] Furthermore, calibration strategies such as matrix-matching calibration and multi-energy calibration (MEC) are commonly employed to minimize the effects of matrix interference.^[40–46]

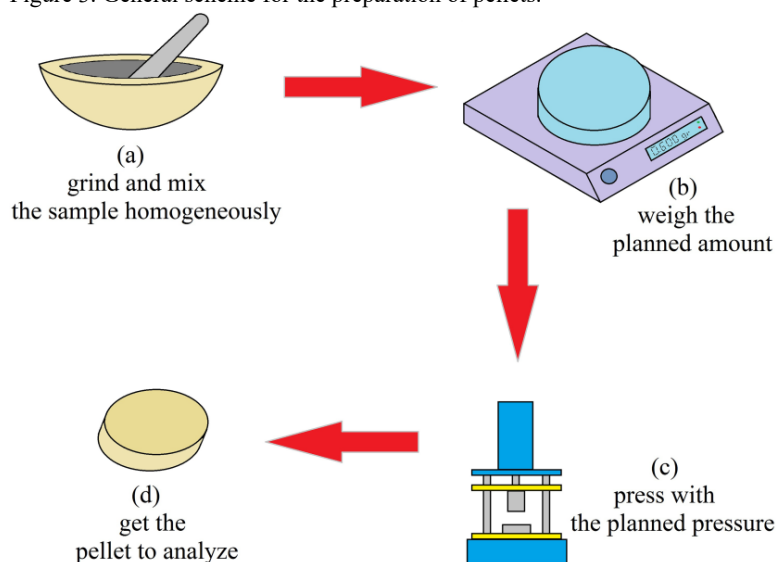
A number of milk derivatives were analyzed by LIBS in the last five years to further optimize working conditions and open new research avenues. Different brands of butter and margarine were analyzed with LIBS to determine the concentrations of macronutrients and compare them with the results obtained from inductively coupled plasma mass spectroscopy (ICP-MS) and flame atomic absorption spectroscopy (FAAS), resulting in an excellent match with a maximum standard deviation of 2.6%.^[47]

Different cheese samples were also analyzed by Ayvaz et al.^[48], whereby samples were crushed and thoroughly mixed in a mortar and pestle, and then the fine powders were stirred in plastic bags at -18°C . These samples were analyzed with LIBS using a Nd:YAG laser coupled to a 5-channel spectrometer. The parameters identified in this study (i.e., percentages of moisture, dry matter, salt, total ash, total protein, pH, fat, acidity, water soluble nitrogen, trichloroacetic acid soluble nitrogen, and phosphotungstic acid) revealed that LIBS can be successfully employed as a standard quality control method.

Meat

Meat samples have been analyzed extensively with LIBS in the last five years, with researchers focusing their attention primarily on beef samples. Beef is typically placed in a hot air drying oven maintained at 105°C for at least 12 h, and then the samples are crushed, mixed homogeneously, and pelleted under $10 \text{ ton}\cdot\text{cm}^{-2}$ pressure to prepare beef samples for LIBS as you can see in Figure 3.

Figure 3. General scheme for the preparation of pellets.



Quantities of Rb, Cu, Na, and K found in beef samples obtained through different calibration models were compared with the results obtained from either atomic absorption spectroscopy (AAS) or graphite furnace atomic absorption spectroscopy (GFAAS), revealing a good match of the results and demonstrating that LIBS is a feasible method for meat analysis with adequate accuracy and precision, thus confirming the potential of LIBS for meat analysis.^[49–51]

Other methods have been used to prepare samples very fast (< 3 h) and very slow (> 70 h), but all of them have established the potential of LIBS to identify adulteration in meat species. The mineral composition of various meats differs and LIBS can distinguish between mineral percentages present in each one.^[52–54] The variation of the CN and C₂ spectral bands to recognize spoilage of meat and the concentration of Ca to determine levels of toxicity can also be determined from LIBS analysis.^[55,56]

Vegetables

Vegetables are an essential component of a balanced diet to promote health benefits in humans. However, it is important to be aware that vegetables may contain a number of toxic heavy metals, toxic organic substances, and toxic inorganic anions (e.g., sulfide or fluoride). Several vegetable samples have been analyzed by LIBS after drying, grinding, and pelleting. PCA is the most common strategy used to determine adulteration in vegetables. For example, PCA was used for the qualitative analysis of pure pistachio, green pea, spinach, and adulterated pistachio samples, successfully discriminating between the samples.^[57] PCA and LIBS spectra have also been used to reveal the level of adulteration in saffron samples^[58] and to identify transgenic maize from non-transgenic maize.^[59]

Multielemental analysis is important to identify a number of elements, such as C, O, N, Mg, Ca, Na, K, Al, Ba, Cr, Cu, P, Fe, Sr, and Zn.^[60,61] These studies have also been employed for the detection of Cd in fresh leaves of contaminated vegetables^[62–64], and to determine the levels of titanium dioxide used as an additive in chickpea samples.^[65]

Wheat flour and secondary products from wheat flour

Wheat flour is one of the most important primary products to prepare a variety of secondary products, such as bread, pasta, and pizza among many others. The growing global population makes the analysis of wheat and its products necessary to maintain human health.^[66] Pellet formation is considered necessary to obtain a homogeneous shooting surface and facilitate sample handling of flour samples. Another method involves burning a food sample under controlled conditions to obtain an ash that is analyzed using LIBS to identify several elements. For instance, wheat flour samples with different ash contents were dried at 105 °C for 2 h and then analyzed with LIBS, indicating a progressive increase in the concentrations of K, Mg, Na, Ca, and Zn in conjunction with an increase of the ash concentration.^[67] A similar increase was observed for K and Mg concentration when comparing non-wheat flours of potato flour, buckwheat flour, brown rice flour, tapioca flour, maize flour, and gluten free flour blends.^[68] For ash analysis in wheat milling fractions, partial least squares (PLS) regression has been employed as a calibration strategy and PCA for data interpretation with a good discrimination analysis percentage.^[69,70]

Various methods have been investigated to determine macro and micronutrients in different food samples. For example Atta et al.^[71] fixed the focal length, delay, and exposure time to evaluate the laser pulse energy to acquire the best signal (100 mJ), obtaining good recovery in percentages of Zn and Fe in wheat flours. A standard addition method has also been used for the direct determination of Ca to distinguish between natural and calcium-added flours with LIBS by implementing a response surface obtained from a full factorial designed experiment using central points from the best instrumental conditions. In both cases, good recovery percentages for analytes were obtained.^[72,73]

Tea

Tea is one of the most common beverages in many countries around the world. Multielemental LIBS analysis of tea leaves is usually performed on tea leaves pressed into pellets prior to analysis.

Fisher discriminant analysis (FDA) was used to develop a variety of statistical inferences based on probability distribution by identifying spectral lines or band intensities of Mg, Mn, Ca, Al, Fe, K, CN, and C₂ with a 95.3% correct average identification rate.^[74] PLS discriminant analysis was employed to transform the high-dimensional data into a

set of a few intermediate linear latent variables (determined by leave-one-out cross-validation). After the minimum-maximum normalization of components, the average of 20 analyses resulted in 99.8% correct identification.^[75]

The identification of macronutrients, micronutrients, and contaminants; determination of calibration strategies; and use of internal and external standard methods for different classes of tea have provided results for comparison with other analytical techniques, ultimately obtaining good recovery percentages for LIBS. Recovery percentages of 92.9% for Ba in peppermint tea samples and 100.8% for K in black tea have been attained.^[76–80]

Fish and seafood

The study of environmental pollution and subsequent contamination of aquatic species is of vital importance since rivers, estuaries, lakes, and oceans receive the flow of pollutants from anthropogenic and industrial activities (e.g., through runoff, rain, and movement of air masses).^[81] Hg and As in aquatic species have been studied extensively with other spectroscopic techniques previously; Pb, Co, and Cu detection with LIBS have been the focus of recent investigations. For example, the determination of these elements was performed using the dried muscle of fish under conditions that allowed the local thermodynamic equilibrium (LTE) to be reached. The results were compared to other techniques and contrasted with reference values, revealing that LIBS is an effective tool for pollutant monitoring in aquatic life samples.^[35,82]

An interesting study was performed by Abdel-Salam et al.^[83], whereby biosynthesized silver nanoparticles were employed to intensify the emission intensity of the spectral lines and thus identify proteins in canned tuna. Another interesting work developed by Chen et al.^[84] evaluated trace elements in cuttlefish, octopus, and sardines using two different delay times; one short delay time to reach the LTE and a longer one to achieve partial plasma equilibrium, thus allowing detection of parts per million (ppm) concentrations of Mg, Ca, As, Si, Zn, Cu, Cd, B, Li, and Sr.

Bivalve mollusks are important bioindicators of water quality in the natural environment due to their filtering capacity. The main macronutrients in bivalve mollusks (Ca, K, Mg, and Na) have therefore been analyzed using direct analysis of solids by LIBS and compared with other techniques such as wavelength dispersive X-ray fluorescence (WDXRF), thus indicating satisfactory accuracy and precision (root-mean-square deviation (RMSD) $\geq 18\%$).^[85,86]

Rice

Rice is a basic food that is consumed in at least in one-third of the world, including many countries of Southeast Asia and South America. Investigations to classify rice according to its geographical origin using LIBS and supported by PCA have been performed to reduce input variables and to reduce the collinearity of LIBS spectral results.^[87–89]

Rice powder mixtures were employed for rapid detection of different contaminants including heavy metals by LIBS. It is generally agreed that 60 mJ laser pulse energy for LIBS is sufficient to obtain the best signal-to-background ratio for rice samples, resulting in good agreement with reference values when Cr, Cd, and Cu are present as contaminants.^[90–93]

Pérez-Rodríguez et al.^[89] used the emission lines of C, Ca, Fe, Mg, and Mo for direct analysis of Argentine brown rice samples using spark discharge-LIBS, while also employing chemometric tools to distinguish rice origin. Utilization of the k-nearest neighbor (k-NN) algorithm resulted in the best performance, providing 84% accuracy, 78% specificity, and 100% sensitivity in the classification of rice samples.

Coffee

Whether by tradition or culture, coffee is one of the most widely consumed beverages worldwide. Several problems related to adulteration, quality, and pollution can be identified with LIBS.^[94] For example, LIBS has been employed for the analysis of inorganic constituents, mainly K, Ca, Mg, and Na. Pellets are usually used for sample preparation in these analyses, either from coffee beans or ground coffee.^[95,96]

When coffee quality is under discussion, it is important to know the differences between different presentations as well as the raw material used. For example, Silva et al.^[97] studied the presence of green, black, and sour beans in

different brands of ground and unroasted coffee by analyzing the emission bands and lines of C, CN, C₂, and N, the results of which were supported by PCA. A similar approach combining LIBS with chemometric analysis was used to verify the presence of wheat, corn, and chickpeas, confirming that LIBS can be combined with chemometric methods to obtain a powerful technique for the accurate and rapid detection of coffee adulteration.^[98]

Edible salt

Sodium chloride, also known as common salt or table salt, is the most widely consumed edible salt used globally for centuries. In 2016 and 2017, a team of researchers from the Department of Chemistry in Mokpo National University simultaneously employed LIBS and laser-ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) to analyze salt samples in order to obtain a multivariate classification of edible salts (sea salt and rock salt) from different sources, while also performing chemometric analysis using a partial least squares discriminant analysis (PLS-DA) model. Furthermore, they also identified elemental sulfur present in similar samples, comparing LIBS, LA-ICP-MS, and laser-ablation inductively coupled plasma optical emission spectrometry (LA-ICP-OES) with ICP-OES recovery percentages, finding a correlation between S and O that is associated with the presence of sulfide (S²⁻) and sulfate (SO₄²⁻).^[99,100]

To demonstrate the ability of LIBS to analyze commercial samples suspected of being contaminated with a toxic salt, Sezer et al.^[101] analyzed meatball samples contaminated with lithium chloride. Dixit et al.^[102] mapped the diffusion of salt in samples of beef fillet, monitoring the intensity of Na emission on the surface of the sample. A ratio of 90 to 90 was sequentially obtained, allowing the generation of a NaCl distribution map for each sample using R and EBI image software packages.

Sugarcane

LIBS studies developed with sugarcane to detect and classify impurities from plant and soil residues can be incorporated during the sugar or alcohol manufacturing process. For the detection of impurities, mixtures of soil and vegetable residues incorporated with cane sugar and immobilized on a polyvinyl alcohol (PVA) substrate were used for analysis in a PCA study supported by chemometric analysis, where a good correlation between Ca and Mg in the samples was observed. Using this same methodology for sample preparation and analysis, contamination ranges were identified with the aid of a partial least-squares discriminant analysis (PLS-DA), thus demonstrating the potential of LIBS to discriminate between different contaminating species.^[103–105]

Water

Water quality is very important to assess in the food industry. However, studies using LIBS for water analysis have been very limited since the strength of the technique lies in the analysis of solid samples. A comparison between natural and seawater samples was performed for the determination of Sr. Samples contaminated with Sr and those that without Sr were analyzed by ICP-OES for comparison. The samples were analyzed in the liquid state in glass cuvettes by applying a low energy laser pulse (8 mJ), and the time between pulses was controlled to avoid bubbling and swelling of the samples. This technique provided good reproducibility and good recovery percentages, although the high salt content affects the electron density during plasma formation.^[106]

One study proposed the feasibility of using LIBS to quantify Cr in water samples by employing ceramic solid supports. The ceramic supports were prepared by pressing 0.35 g of ceramic with 0.15 g of cellulose at 8 ton·cm⁻² for 5 min. The ceramics were then treated with water with different Cr salts and Fe(II) sulfate heptahydrate added for the reduction of Cr(VI) to Cr(III). The ceramic selectively adsorbs Cr(III) species at pH 7; quantification of the Cr(VI) species by LIBS was possible after reduction of this species to Cr(III) using Fe(II) as the reducing agent.^[107]

Other foods

Miscellaneous types of food samples that have only been the subject of sporadic studies but can be a starting point for future work are described here. For instance, vegetable oils were investigated by studying the C₂ bands of liquid samples, indicating the presence of carbon-carbon double bonds that were correlated to the concentration of oil but not the number of double bonds.^[108]

A study was conducted by examining the emission of Na at 589 nm to quantify sodium chloride in bakery products used to prepare bread, which were dried and pelletized for LIBS analysis, the results of which were positively validated with reference methods.^[109] Another study was performed with different brands of bread to detect Br from the atomic transition line at 827.2 nm. Dried and pulverized samples were spiked with different concentrations of Br and then samples were pelletized for analysis. The resulting values were very close to those measured with the reference ICP-MS technique.^[110] An interesting work on the analysis of Pb and other elements present in edible food coloring revealed 4 to 8.8 mg·kg⁻¹ of Pb present in the samples, which was confirmed with an ICP-OES reference, thus demonstrating the potential of LIBS as a food security tool.^[111]

Investigations on alcohol and tobacco

Although they are not part of a regular diet, the consumption of alcoholic drinks and use of tobacco is very common throughout the world. Historically, many people use these products before, during, or after food consumption, requiring analysis and control of their components.

For example, Moncayo et al.^[112] were able to use LIBS to classify red wines according to their origin, preparing samples with collagen to form a gel and then using a correlation model to predict each wine group. Another study was performed to determine the presence of Cu in cachaça using paper disks for LIBS analysis. Very good results were obtained, thus showing promise for adaptation of this technique to analyze other contaminants such as lead.^[113] Tobacco samples for multi-elemental analysis have been prepared by forming pellets or with intact leaves for comparison with other spectrometric reference techniques. These novel approaches that have been implemented reveal the potential of LIBS for the analysis of alcohol and tobacco.^[114–116]

Growing trends for LIBS in food analysis

Spectroscopic techniques are frequently used for quality control, testing of raw materials, and determination of contamination in the food industry. The food industry has been in need of a rapid, simple, cost-effective, and portable technique with minimum sample preparation for a number of years. LIBS has been demonstrated to fulfill all of these requirements, proving useful as a technique for the analysis of grains, vegetables, salts, alcoholic beverages, tobacco, sugar, meat, fish, coffee, tea, and water samples. The LIBS technique is not only valuable for micronutrient and major element detection, but also for the detection of toxic contaminants. LIBS is comparable to established analytical methods in terms of precision, accuracy, and sensitivity, but is more advantageous in terms of speed and ease of sample preparation.

Efforts are underway to evaluate and develop calibration strategies that minimize or overcome the strong matrix effects that may compromise the analytical parameters of the method and preclude determination with satisfactory accuracy and precision for quantitative food analysis with LIBS. We have just begun to explore the full potential of LIBS in the food industry, focusing mainly on the classification of foods by specific groups or by their origin, and in the detection and quantification of macronutrients and specific elements that can be considered toxic according to their concentration.

A growing demand in the field of food safety has led to the development of spectroscopic techniques for prevention, control, and remediation measures, and it is in this realm that LIBS has performed exceptionally strong. Although some challenges remain, such as manipulating liquid samples, there is much promise in the application of LIBS in the food industry thanks to the ease of equipment handling, the facile preparation of samples, and the versatility in its use. LIBS research has been performed on the laboratory scale thus far, but we believe that in the coming years LIBS instrumentation will begin to be employed in the food industry as research in this area progresses.

Declaration of interest statement

The authors declare that there are no conflicts of interest.

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