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Spectroscopic assessment and quantitative analysis of the trace element composition of vegetable additives to meat products

Igor Palamarchuk, Fu Yuanxia, Dmytro Zhuravel, Ievgenii Petrychenko, Roksolana Blishch, Anatoliy Holovatyuk, Olexander Domin, Tatiana Kostiuk

ABSTRACT

In this scientific work, using the method of laser-induced breakdown spectroscopy (LIBS), the spectra of beef samples and impurities in meat products, namely, banana, pineapple, kiwi, bergamot, poria coconut, Chinese angelica, chicken blood vine, were measured by using developed experimental devices. The purpose of the research was to evaluate the qualitative characteristics of additives to meat semi-finished products for the potential formation of the desired properties of the products due to the analysis of the received spectrograms of trace elements of the samples when applying the LIBS method, quantitative analysis for processing the received information. The determined values of the electron temperature of the plasma, the electron density of the used raw material samples, and the assessment of the local heat balance were used as evaluation criteria. When processing the obtained data, the characteristics of the laser-induced plasma surface of the presented samples were analyzed; the electron temperature and electron density were determined, and a quantitative analysis of trace elements was carried out. LIBS technology allows rapid real-time monitoring and qualitative analysis of trace elements online and over long distances. During the research, it turned out that quantitative analysis requires further study and optimisation of experimental conditions, such as pre-treatment of samples. These conditions optimise defocusing, double laser pulse, and sample temperature, which increases the signal/noise ratio of all spectral lines. The combination of fluorescence spectroscopy and Raman technology enables higher detection sensitivity and better molecule control, creating a quantitative analysis method model that can reduce matrix effects and overcome the self-absorption effect. Among the difficulties of using LIBS technology, several elements can be noted online simultaneously, compared to Raman. The combination of spectroscopy and fluorescence spectroscopy can obtain more comprehensive information about the composition of materials, which can become a potential platform for monitoring trace elements in food products.

Keywords: laser-induced spectroscopy, radiation spectrum, impurities in meat products, detection limit, quantitative analysis of spectrograms

INTRODUCTION

Trends in improving the quality characteristics of food products promote the development of new food technologies and products using plant and animal-based additives. When developing new, highly effective varieties of meat products, particularly sausages, sausages, anchovies, and other products, it is practically impossible to bypass the use of these components in modern technologies. Elements of cereal and vegetable raw materials are becoming more and more widespread as a source of vitamins and useful microelements that affect the digestion process and the release of harmful toxic substances from the body due to their relatively low-calorie content **[1]**, **[2]**. Additions of wheat fiber with pumpkin pectin have revealed unique hydrophilic properties and the ability to form emulsions, increasing sausages' functional-technological and structural-mechanical properties **[3]**, **[4]**. In general, fruits, vegetables, and cereals are characterized by a sufficiently high content of vitamin C, iron, magnesium, phosphorus, and other elements, which allows, when added to meat semi-finished products, to create food products with improved organoleptic indicators and increased biological value **[5]**, **[6]**.

The evaluation of the elemental composition of beef and the used impurities of banana, pineapple, angelica, bergamot, leek, and chicken blood vine carried out in this work was based on the use of the method of laser-induced breakdown spectroscopy (LIBS) **[7]**, **[8]**. The essence of this method is that the sample's surface is irradiated with a sufficiently high-density laser beam. As a result, it evaporates, and neutral and ionic substances are formed in excited states. Excited particle emission spectra confirm sample composition and trace concentration quantitatively. Solid, gaseous, and liquid substances can be used as research objects. The main advantages of this technique include minimal destruction of samples, the possibility of online analysis, remote processing of research results, and determination of data in conditions of high temperatures and aggressive environments, which is often impossible to implement with traditional methods of chemical analysis. Such potential opportunities make it possible to successfully use LIBS technologies in many fields of industrial implementation and theoretical research, in particular, in materials science, chemistry, biochemistry, medicine, archeology, metallurgy, ecology, evaluation of food products, etc. **[9]**, **[10]**.

The purpose of the research was to determine the trace element composition of admixtures to meat semi-finished products for the potential formation of the required product properties by using laser-induced breakdown spectroscopy, theoretical methods of processing the obtained results when determining the electron temperature of the plasma, the electron density of the used samples of raw materials and assessing the local heat balance.

Scientific Hypothesis

The main scientific hypothesis of this scientific work is the adequacy of assessment of the technological, biological, and ecological value of edible meat products based on the results of spectrographic and quantitative analysis of samples of plant impurities; that is, with the help of the technology of laser-induced plasma spectroscopy and according to the results of research, the formed plasma on the surface of the sample can be fairly quickly and qualitatively assessed the trace elemental state of solid, liquid and gaseous substances, regardless of the shape of the object, which shows the effectiveness of the impurities used in the preparation of recipes, meat semi-finished products.

MATERIAL AND METHODOLOGY

Samples

The following samples of food products were used for experimental research: coconut poria (Figure 1a), Chinese angelica (Figure 1b), bergamot (Figure 1c), chicken blood vine (Figure 1d), banana, pineapple, kiwi, and beef. These materials were produced as flakes by preliminary washing, cleaning, grinding, and subsequent drying. The presented components are finely ground to powder to prepare sausage fillers.

Chemicals

Ethylenediaminetetraacetate (EDTA), (country of manufacture China).

Potassium permanganate ($KMnO_4$), (country of manufacture China).

Sodium sulfide (Na_2S), (country of manufacture China).

Water (H_2O), (country of manufacture China).

Animals, Plants, and Biological Materials

The following were used for research: banana (*Musa*), pineapple (*Ananas comosus*), and kiwi (*Actinidia deliciosa*).

Medicinal plants: bergamot (*Citrus bergamia*), coco poria (*Poria cocos*), Chinese angelica (*Angélica*), chicken blood vine (*Spatholobi caulis*).

Beef (boneless beef of the first grade, in which muscle tissue with a mass fraction of connective and fatty tissue did not exceed 7%) (bought in the supermarket Kaoshan Road, Anhui, China).

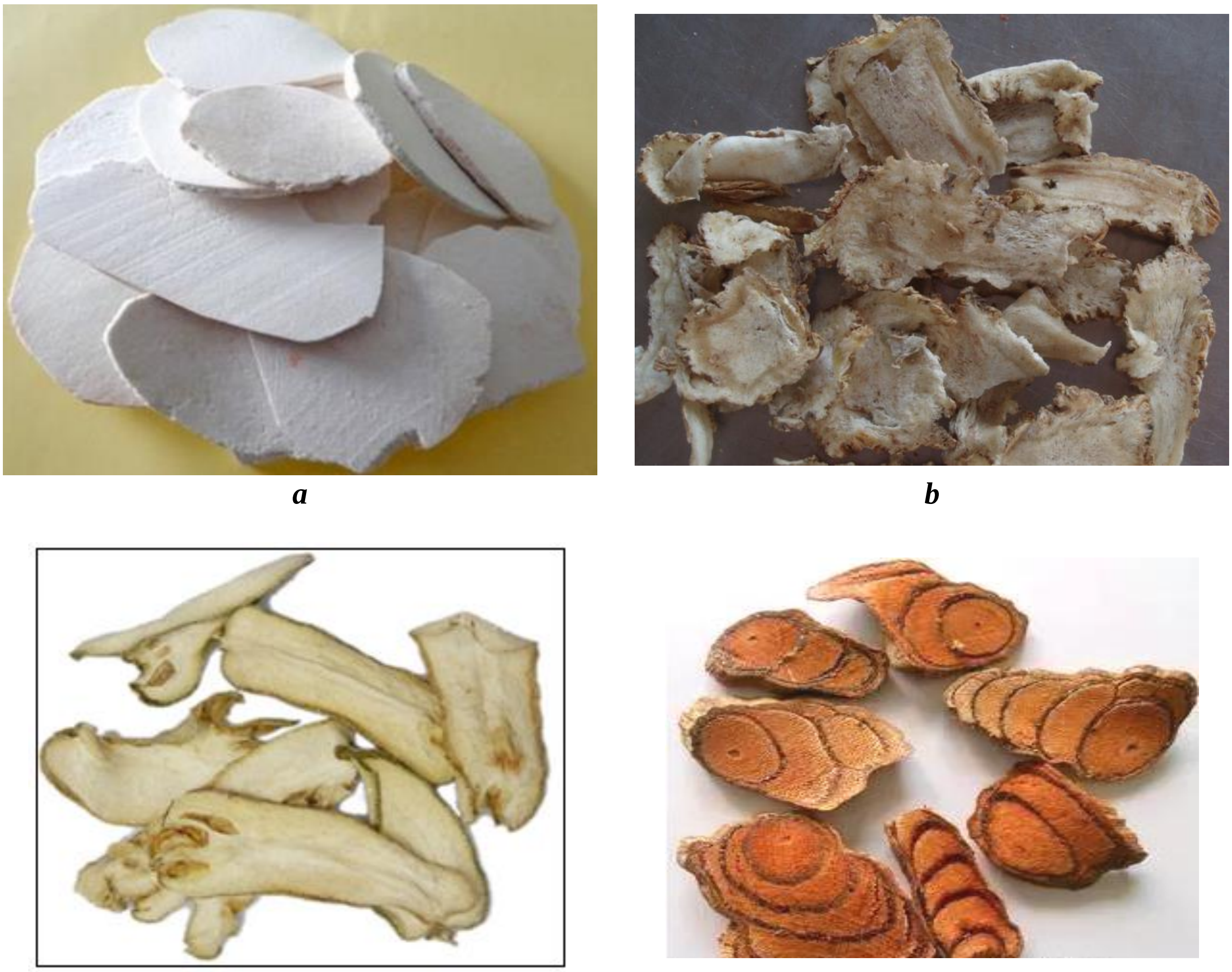
Instruments

The main elements of LIBS experimental equipment include lasers, digital delay pulse generators, ICCD spectrometers, light collectors, focusing lenses, sample holders, and computers (Figure 2).

Slicer (HURAKAN HKN-HM250M), (country of manufacture China).

Laboratory dryer (DZF PK), (country of manufacture China).

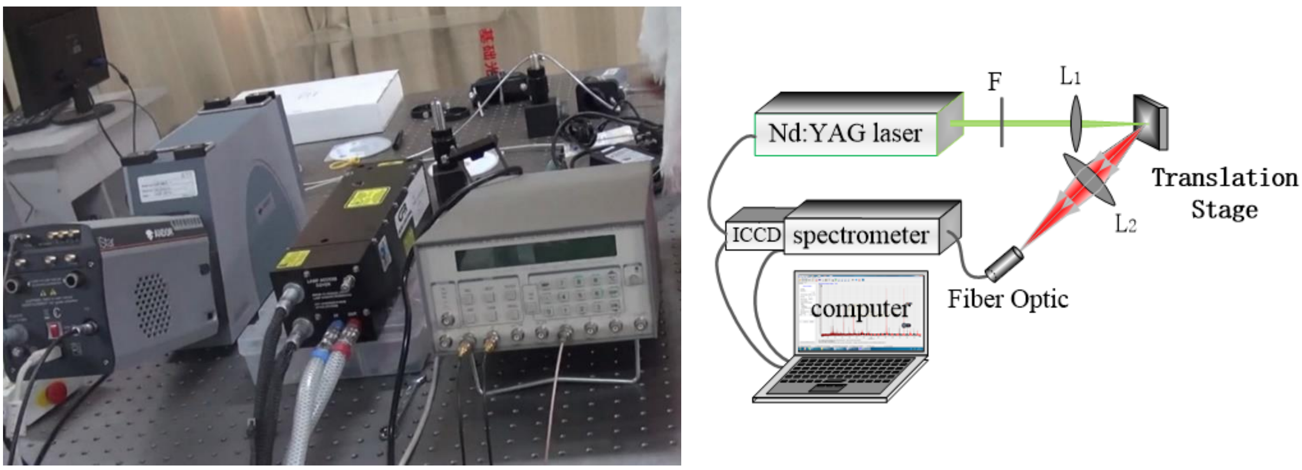
Colloid mill (Vektor-FDM-Z-150), (country of manufacture China).



a b

c d

Figure 1 Form of prepared samples. Note: a – samples of poria coco; b – samples of Chinese angelica; c – samples of bergamot; d – samples of chicken blood vine.



a b

Figure 2 Experimental equipment for the implementation of the method of laser-induced plasma spectroscopy. Notes: a – experimental spectroscope model; b – structural diagram of the equipment.

Laboratory Methods

The research is based on the method of laser-induced breakdown spectroscopy (LIBS), which allows elemental analysis of the substance **[11]**, **[12]**.

The inclined Boltzmann line method was used to calculate the plasma's electron temperature **[13]**, **[14]**. The current evaluation methods are the standard sample calibration method, the internal standard method, the standard addition method, and the free calibration method (CFLIBS) **[15]**.

When performing a quantitative analysis of the experiment's results, the following were used: the Stark expansion method for determining the electron density of the plasma and the free calibration method **[16]**.

Description of the Experiment

Sample preparation: Before starting the research, the used samples were subjected to the following preliminary treatment: washing and cleaning, cutting into thin slices 3-4 mm thick, and drying was carried out on a laboratory drying unit (Figure 3), which allows maintaining a constant temperature in the working drying area.

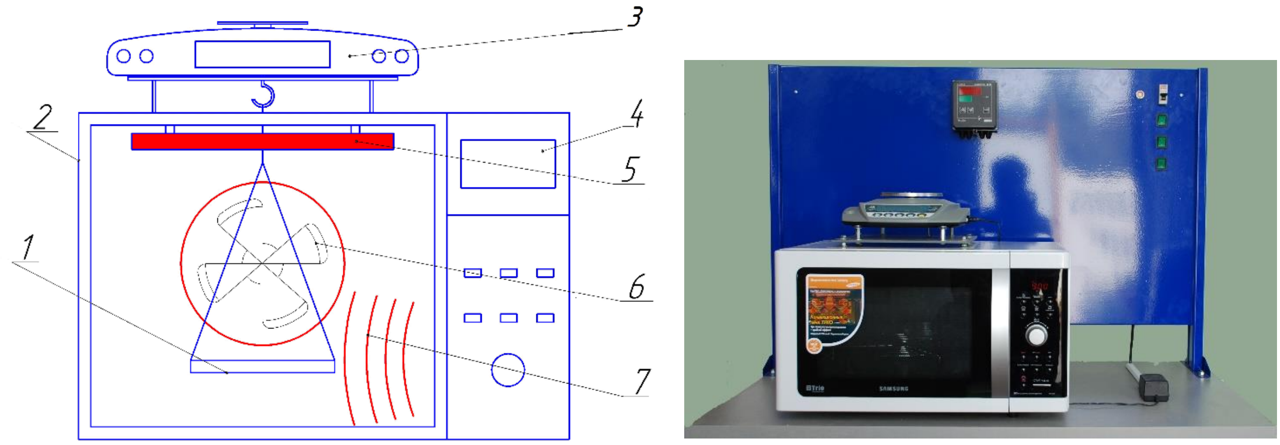


Figure 3 The scheme of the laboratory installation: 1 – bowl with dried material, 2 – camera, 3 – electronic scales, 4 – temperature indicator, 5 – IR heater, 6 – convection heating, 7 – microwave heating.

The drying process was carried out at 70, 80, 90 °C for circles and 90, 100, 110 °C for pieces. This temperature range was chosen because it is impractical to dry samples below 70 °C due to the significant duration of the process and high energy costs. For samples cut into pieces, temperatures above 110 °C lead to a sharp change in color. The beef samples were to be washed, surface cleaned, and cut into slices of 9-10 mm.

Number of samples analyzed: Five samples of beef and six samples of each vegetable additive were used during the experiment.

Number of repeated analyses: 5 repetitions of the analysis were carried out for beef and 6 repetitions for each vegetable additive.

Number of experiment replications: The experiment was repeated five times.

Design of the experiment: During the preparation of the samples, washing, and cleaning of the surface coating, cutting into thin slices, and drying (for plant impurities) were carried out sequentially. The beam generated by the Nd: YAG laser is focused on the samples through a lens. The sample in the focus zone undergoes multiphoton ionization to generate free electrons, followed by avalanche ionization to produce a certain amount of plasma. The plasma radiation spectrum is received by an optical receiver and transmitted to the spectrometer through an optical fiber. The spectrometer separates the collected spectrum by performing ICCD spectroscopy. Next, the collected optical signal is converted into amplified electrical signals, which are already perceived by the computer and displayed as a spectrum diagram of the components.

An ND:YAG laser initiated the ablation process, which enabled second harmonic generation. The radiation parameters were: wavelength up to 532 nm, frequency up to 10 Hz, pulse duration of 8 ns. The monochromator had a 1200 grooves/mm grating and an inverse linear dispersion of 0.1 nm. The resulting time-resolved LIB radiation was fed to an SRS250 model integrator for signal processing.

When applying the Boltzmann slant line method **[17]**, **[18]**, the following steps were performed to calculate the electron temperature. The analysis lines were chosen to belong to the same element, had the same ionization order, had better isolation, a higher signal-to-noise ratio, no self-absorption, and took the largest possible differences in excitation energy levels for evaluation.

When performing a quantitative analysis of the experimental results, the following were used: the double-line Boltzmann method for calculating the electron temperature of the plasma, the Stark expansion method for determining the electron density of the plasma, and the free calibration method. In the absence of elements of standard samples with a known content, which was ineffective for fruits, the CFLIBS-free calibration method was used. In this way, the conditions of LTE local thermal equilibrium were achieved.

Statistical Analysis

The results were evaluated using statistical software Statgraphics Centurion XVII (StatPoint, USA) – multifactor analysis of variance (MANOVA), LSD test. Statistical processing was performed in Microsoft Excel 2016 in combination with XLSTAT. Values were estimated using mean and standard deviations. The reliability of the research results was assessed according to the Student's test at a significance level of $p \leq 0.05$.

RESULTS AND DISCUSSION

Discussion of the subject and object of research

Impurities of substances containing pectins create a sufficiently pronounced radioprotective effect **[19]**, protecting the population from the accumulation of radionuclides in the body due to the formation of gels in the presence of organic acids and sugars **[20]**. Ingredients from fucus seaweed and wheat germ, spirulina seaweed with pumpkin oil, nutmeg, or cardamom in the technology of cooked sausages allow to enrich the food product with such biologically active substances as iodine, alginic acids, various vitamins in the studies of Pogorelova and Yakymenko **[21]**. High functional and organoleptic properties of cooked sausages were obtained by the introduction of a multifunctional additive based on animal protein, alginate, carrageenan, guar gum, and xanthine gum, which is substantiated in the scientific works of Vinnikova **[22]**. A composite supplement with elements of essential oils of cornflowers, rosemary, laurel, marjoram oil, lactose, and ascorbic acid provided high organoleptic indicators according to research by Yeresko **[23]**.

In the works of Bal-Prylypko, it was proved that the use of a bacterial preparation based on the denitrifying microorganisms *Staphylococcus carnosus*, *S. carnosus subsp. utilis* in the brine composition made it possible to form high organoleptic properties in sausage products and increase their nutritional value **[24]**, **[25]**. It is with the use of plant additives that the production of meat products of increased biological value with increased protein content, normalization of acidity in the human body, increased digestibility of products, ensuring the optimal ratio of protein and fat, vitamins and mineral elements is ensured, which forms the basis for the implementation of the theory of balanced nutrition according to the formulation of Maksimov **[26]**.

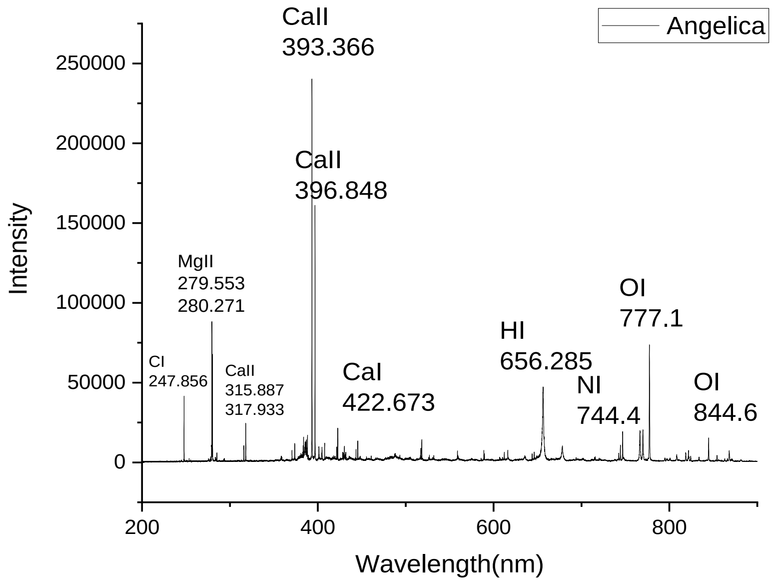
Laser-induced plasma spectroscopy uses laser pulses as energy sources and lenses to focus the laser on the sample surface. According to the research results, this technology can detect the microelemental state of solid, liquid, and gaseous substances, regardless of the object's shape **[27]**, **[28]**.

Many researchers used laser-induced plasma spectroscopy not only to analyze the composition of trace elements but also to carry out qualitative and quantitative analyses of elements of heavy metals, research various processing algorithms, plan multifunctional experiments, and constantly improve experimental devices **[29]**. Li from Jiangxi Agricultural University analyzed the metal elements contained in pericarps and pulp of tangerines and navel oranges in this way **[30]**. Abdul Jabbar and his scientific colleagues from Milpur University of Science and Technology used laser-induced plasma spectroscopy to study the elemental composition of roots, stems, seeds, and other parts of rice **[31]**. The studies proved the broad prospects of using laser-induced plasma spectroscopy to assess the quality of raw materials, semi-finished products, and finished products in food and processing industries **[32]**.

Evaluation of the microelement composition of the studied beef samples and plant impurities

In assessing the microelement composition of the samples of the products presented above, spectrograms were obtained using the method of laser-induced breakdown spectroscopy (Figures 4, 5, 6, and 7). The "intensity" parameter, which shows the intensity of the plasma radiation spectrum of the experimental test sample, was plotted along the ordinate axis. Figures 4, 5, 6, and 7 show the different wavelengths that calibrate different elements, and the characteristic wavelengths of the elements can be requested according to the "NIST: Atomic Spectra Database Row Form". The peak intensity corresponding to different wavelengths is related to many factors, such as the possibility of the transition of energy levels of atoms or ions, the structure of the energy levels of the excitation energy, the composition of the sample (the content of elements), the experimental conditions (laser energy, laser focus on surface defocus of the sample, spread spectrum of the ICCD data, delay, slit width or spectrometer dip, etc.

The LIBS spectrogram for Chinese angelica (Figure 4a) revealed the presence of such elements as calcium, magnesium, hydrogen, oxygen, and nitrogen; the calcium content was almost 2.5 times higher than that of other components. Calcium provides the necessary functional properties of bones, joints, and teeth, mainly in the composition of calcium hydroxy phosphate. Regarding the trace element composition of kiwi (Figure 4b), compared to angelica, additional iron and sodium were observed, albeit in small amounts; the calcium content exceeds the content of other components by almost 3 times. Trace elements of iron in the human body are mainly involved in forming hemoglobin, which contributes to blood formation. Sodium is a macroelement in the human body, practically irreplaceable in the extracellular fluid.



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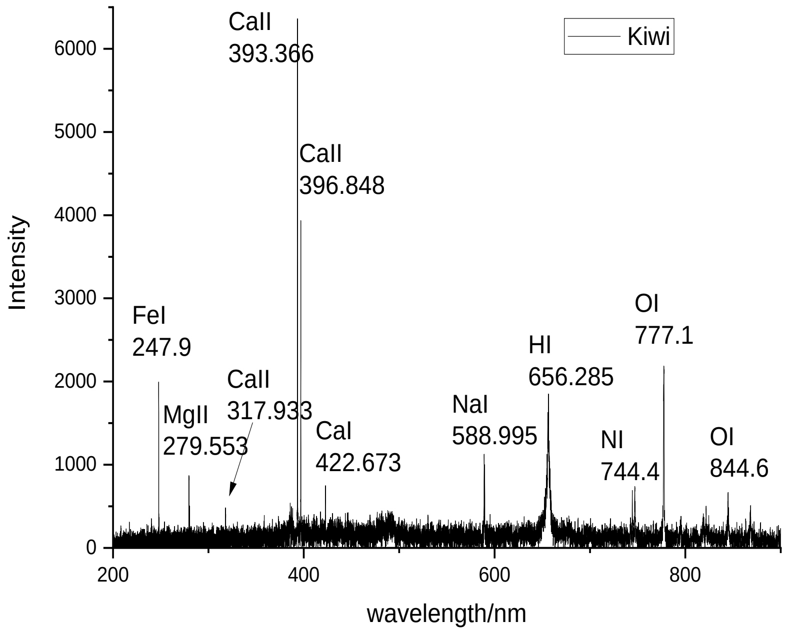
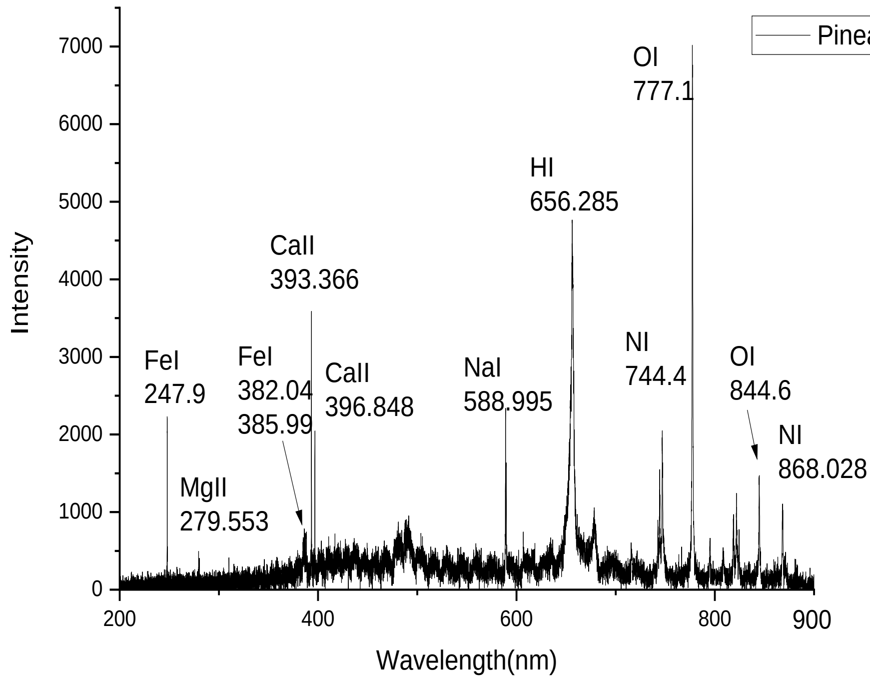


b)

Figure 4 LIBS spectrum of trace elements of vegetable additives to beef in the range of 200-900 nm: a – for the admixture of Chinese angelica; b – for kiwi admixture.

According to LIBS results for pineapple (Figure 5a), the content of calcium, magnesium, iron, and sodium is almost at the same level; the content of hydrogen and oxygen gases turned out to be somewhat higher than that of metals, and nitrogen was almost 2.5-3 times less. The trace element composition of beef practically does not contain metals (Figure 5b), which proves the need to introduce useful metal components into this product using the studied plant impurities.



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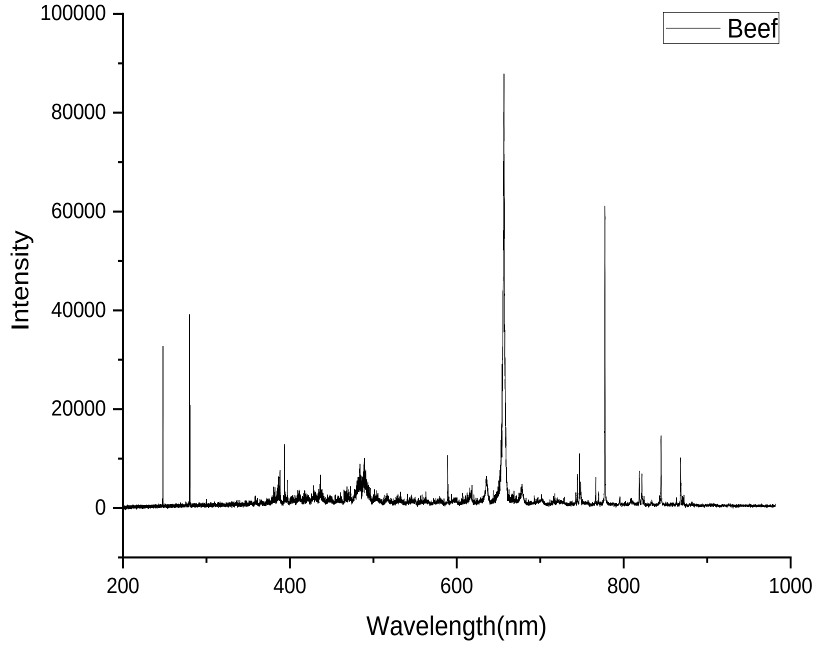
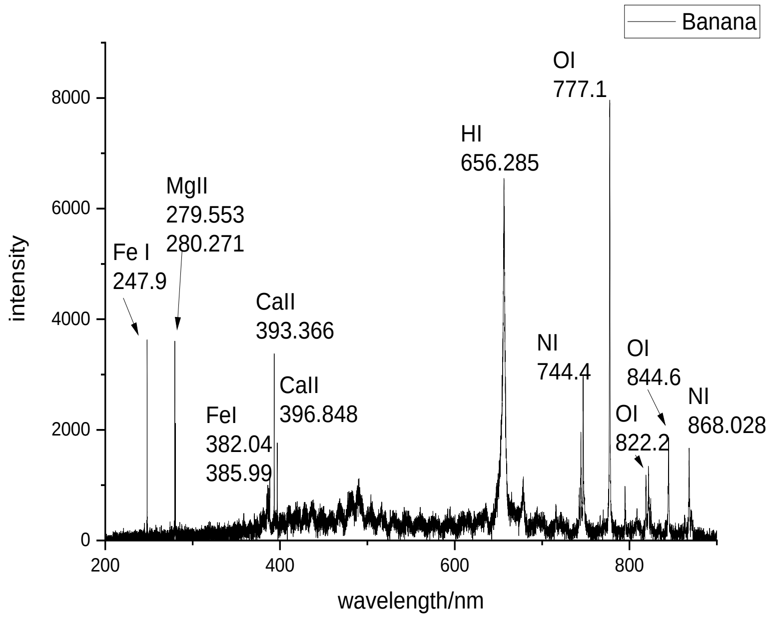


b)

Figure 5 LIBS spectrum of microelements of plant impurities and beef in the range of 200-900 nm: a – for pineapple admixture; b – for beef.

Evaluation of the LIBS spectrogram for a banana sample (Figure 6a) revealed a relatively high magnesium and iron content among metals and oxygen and hydrogen among gases. Magnesium contained in the human body is one of the biologically irreplaceable nutrients. In the bergamot sample, calcium is predominant in terms of content, sodium is much smaller, other metals were not observed (Figure 6b), and a small amount of oxygen, hydrogen, and nitrogen was found among the gases.



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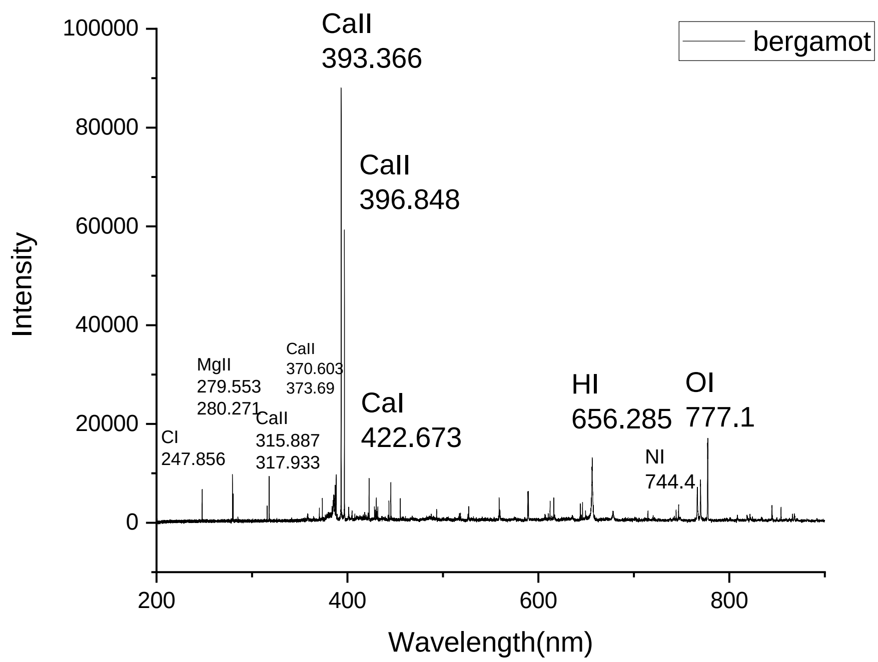
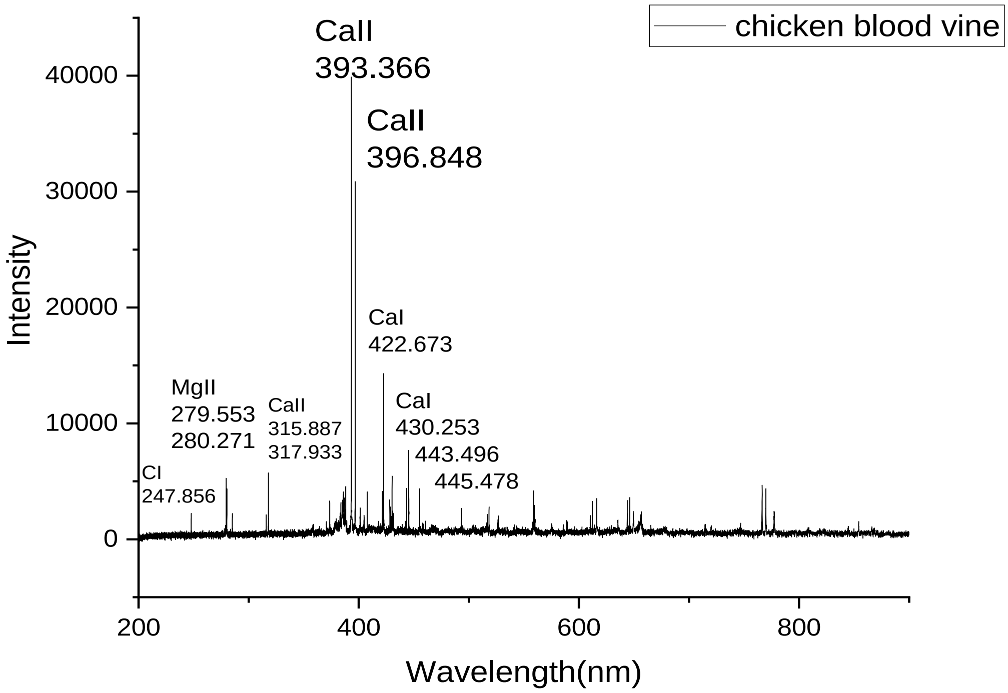


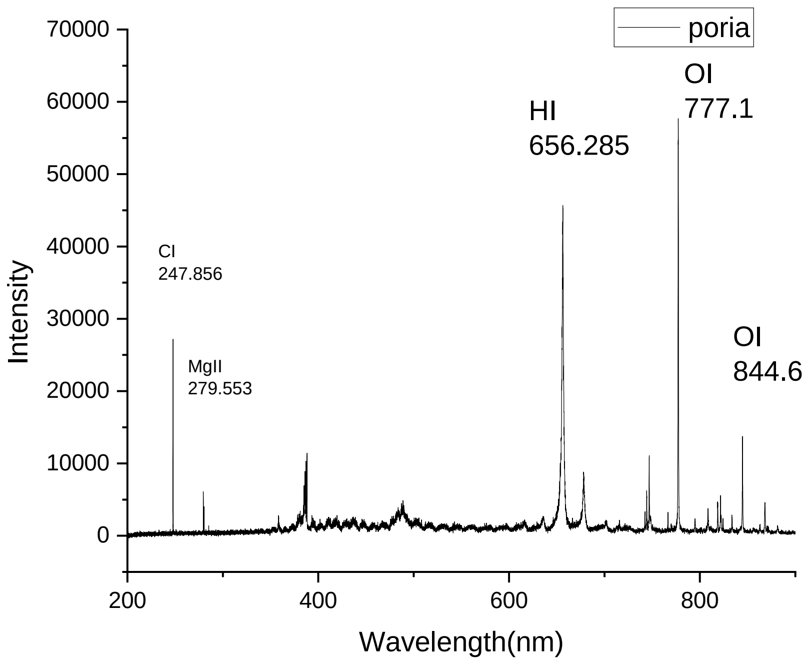
b)

Figure 6 LIBS spectrum of trace elements of vegetable additives to beef in the range of 200-900 nm: a – for banana admixture; b – for the admixture of bergamot.

The LIBS spectrogram for a sample of chicken blood vine (Figure 7a) showed the presence of calcium and magnesium in it; the calcium content was more than 2.5 times higher. Regarding the trace element composition of the coconut poria sample (Figure 7b), the presence of carbon and a small amount of magnesium was observed. Among the gases, oxygen and hydrogen were found in almost equal proportions.



a)



b)

Figure 7 LIBS spectrum of trace elements of vegetable additives to beef in the range of 200-900 nm: a – for the admixture of chicken blood vine; b – for the admixture of poria coconut.

Determination of the main characteristics of plasma

The electron temperature and electron density were calculated to analyse the plasma's characteristics. When calculating the electron temperature of the plasma, you can use the double line method and the inclined Boltzmann method **[13]**, **[14]**, the Sach-Boltzmann method **[33]**, the multi-element Sach-Boltzmann curve method, the characteristic spectral line, and the continuum ratio method **[34]**. Under the condition of local thermal equilibrium (LTE), the formula of the Boltzmann slope method has the form:

$$\ln\left(\frac{I\lambda}{g_m A}\right) = -\frac{E_m}{k_B T} + C \quad (1)$$

Where:
I – the intensity of the spectral line of the relative intensity obtained by Lorentz fitting, Em is the excitation energy, A – is the transition probability of the energy level, g_m is – weighting factor of the upper energy level, k_B – Boltzmann constant, T – electronic temperature, C – coefficient that takes into account the content individual components and their total sum corresponding to the spectral line.

When plotting along the abscissa axis, the excitation energy Em was plotted, and along the ordinate axis – the value $\ln\left(\frac{I_m \lambda_m}{g_m A_m}\right)$

As a result, we obtained the corresponding inclination angle, using which the electron temperature T was determined.

Table 1 shows the wavelength, excitation energy, the weighting factor of the upper energy level, the product of the transition probability of the four spectral lines of CaII, the spectral line's precision, and the transition's energy level. The weaker spectral lines at 317.933 nm and 373.69 nm are selected based on the experimental intensity and the fitted linear correlation coefficient. Therefore, the error in the electron temperature obtained by fitting two different spectral lines of the excitation energy is sufficiently large. The electronic surface plasma temperatures of banana, pineapple, and kiwi were calculated from the slope at 11606 K, 10811 K, and 10685 K, respectively. The electronic temperatures of these fruits have a small difference. When calculating the plasma electron density, the most common method is the Stark expansion for the "H" spectral line and the "non-H" spectral line.

Table 1 Corresponding parameters of spectral lines.

Wavelength (nm)	Excitation energy (eV)	$g_mA(10^8s^{-1})$	Precision	Transition energy level
393.366	3.150984	5.88	C	$3p^64s$ (^2S) -$3p^64p$ ($^2P°$)
396.848	3.123349	2.80	C	$3p^64s$ (^2S) -$3p^64p$ ($^2P°$)
373.69	6.467875	3.40	C	$3p^64p$ ($^2P°$) -$3p^65s$ (^2S)
317.933	7.049551	22.00	C	$3p^64p$($^2P°$) -$3p^64d$ (^2D)

The method of calculating the H-spectral Stark line using the Sach-Boltzmann equation is presented in the following formulas (2), (3), and (4):

$$n_e(H_\alpha) = 8.02 \times 10^{12} \left(\frac{\Delta\lambda}{\alpha}\right)^{3/2} cm^3 \quad (2)$$

Where:
Δλ – full width at half maximum line H_α, n_e – electron density of plasma, α – ionic expansion parameter **[14]**:

$$\Delta\lambda = \left[1 + 1.75 \cdot 10^{-4} n_e^{1/4} \alpha (1 - 0.068 n_e^{1/6} T_e^{-1/2})\right] \cdot 10^{-16} w n_e \quad (3)$$

Where:
T_e – temperature of electrons in plasma, *w* – electron collision coefficient, α - parameter of ionic expansion, which can be found in the paper **[38]**:

$$\frac{I_1}{I_2} = \frac{A_1 g_1 \lambda_2}{A_2 g_2 \lambda_1} \frac{2(2\pi m_e k)^{3/2}}{h^3} \frac{1}{n_e} T^{3/2} \exp\left(-\frac{E_1 - E_2 + E_{1P} - \Delta E}{kT}\right) \quad (4)$$

Where:
subscripts 1 and 2, respectively, represent high and low orders in adjacent ionization orders, m_e – electron rest mass, *h* – Planck's constant, E_{IP} – Ionization energy; ΔE – correction value of ionization energy; n_e – electron density.

By fitting the starting point to obtain the half-maximum width of the spectrum and the electron temperature Te, the electron density ne can be obtained. The effect of ion broadening is much smaller than that of electronic broadening. Therefore, the method of broadening the Stark spectral lines "not H" is simplified to the formula 5:

$$\Delta\lambda = 2w\left(\frac{n_e}{10^{16}}\right) \tag{5}$$

Table 2 shows the results determined using the H-spectral Stark line-broadening method, the H-spectral Stark line-broadening method, and the method of the Sach-Boltzmann equation.

Table 2 Results of electron density calculation.

Method	Select the spectral line and wavelength (nm)	Electron density of banana ($\times10^{16}$ cm^3)	Electron density of Pineapple ($\times10^{16}$ cm^3)	Electron density of Kiwi ($\times10^{16}$ cm^3)
Stark expansion "H" - spectral line	656.285	7.2	7.8	6.8
"not H" - spectral line Stark broadening	CaII393.366	2.937	3.312	3.197
	CaII396.848	2.964	3.273	2.934
	MgII279.553	0.603	0.778	0.529
	MgII280.271	0.584	0.711	0.4972
	NaI588.9	--	7.366	9.749
Saha-Boltzmann equation	CaII393.366 CaII396.848 CaI422.673	6.41	2.35	1.50

In the process of calculating the electron density, it was found that for samples of banana, pineapple, poria coconut, and beef with a high content of oxygen and hydrogen, more significant self-absorption is observed, which is mainly determined by the influence of atmospheric air. The electron density obtained from the CaII and MgII lines in the "H" spectral line broadening method differs by an order of magnitude, which may be due to the low signal-to-noise ratio for the magnesium spectral line, as well as a large fitting error.

The calculation results of different lines of analysis turned out to be quite different, which may be because the plasma does not correspond to LTE during the spectrum measurement. When using the multi-element Sach-Boltzmann equation to determine the electron density, it was not possible to ensure the correct determination of the electron temperature; the content of each element in the fruit is unknown. Therefore, the use of this method is not appropriate.

Quantitative analysis of the studied samples

Calculation formulas for electron temperature and plasma electron density were formulated under conditions of local thermal equilibrium, and calculation data were obtained in optically thin conditions. Under local thermal equilibrium (LTE), the particle velocity satisfies the Maxwell distribution, obeys the Boltzmann distribution at different energy levels, satisfies the Sach equation at different ionisation states, and Planck's law for the radiation density **[35]**. In carrying out this assessment, it was considered that the plasma is infinitely close to the local thermal equilibrium for a certain delay time. The necessary condition for ensuring such a state can be expressed by the following dependence **[36]**:

$$\mathrm{N}_e \geq 1.4\times10^{12} T^{1/2} (E_m - E_n)^3 cm^{-3} \tag{6}$$

The maximum difference in energy levels in this study is 7.05 eV; Electronic Temperature T_e – about 1 eV, and the density of electrons that can be obtained by formula (6) turned out to be greater than the value of $4.9\cdot10^{14}$ cm^{-3}. Thus, the calculated electron density corresponds to the condition of local thermal equilibrium.

The assessment of optical fineness was carried out using the following formula:

$$\frac{I_1}{I_2} = \frac{\lambda_2 A_{K1} g_1}{\lambda_1 A_{k2} g_2} \exp\left[\frac{E_{K1} - E_{K2}}{K_B T}\right] \tag{7}$$

Where: λ_1 and λ_2 are the wavelengths of two spectral lines of the same ionization order for the same element under study

Formula (7) used the parameter values 393.366 nm and 396.848 nm, which have approximately the same excitation energies as those of the studied banana, pineapple, and kiwi samples. The calculation results found that for the studied conditions, the plasmon satisfies the characteristics of an optically thin state at the time of measurement.

For the quantitative analysis of the studied impurities in meat products, it was quite difficult to make standard samples that correspond to the matrix. To comply with this condition, as a rule, elements with known concentrations are added to create a calibration curve that corresponds to intensity and concentration. However, the preliminary processing was quite cumbersome, and the matrix effect was insurmountable. Quantitative analysis was carried out using special data processing methods. In the absence of elements of standard samples with known content, the CFLIBS-free calibration method was used. Then, under the conditions of local thermal equilibrium of LTE and the absence of self-absorption, the dependence was us:

$$\overline{I_{\lambda}^{ki}}\lambda = FC_s A_{ki} \frac{g_k e^{-(E_i/K_B T)}}{U_s(T)} \tag{8}$$

Where: $\overline{I_{\lambda}^{ki}}$ – analysis line intensity, C_s – atomic content corresponding to the line of analysis, F – experimental parameter.

The parameters A_{ki}, E_k, g_k, and the compatible function $U_s(T)$ were obtained from the NIST database, and the parameters F, C_s, and T – were through experimental data processing. The corresponding particle content was obtained by transforming the point of intersection of the Boltzmann slope in formula (1). Then, by summing up the content of atoms and ions, which were determined by the Boltzmann slope of different orders of ionization, the content of the element was obtained. The experimental parameter F was determined by normalizing the content of all elements.

During research, it was observed that when measuring organic samples, such as fruits, it is difficult to detect the spectral lines of all elements that can correspond to the Boltzmann slope.

In scientific works **[37]**, **[38]** the results of the analysis of the microelement composition of meat products to which various kinds of impurities of plant origin were added are given. According to the results of the research, the content of metals in the composition of beef is practically absent. However, the authors emphasize the need to introduce such components into finished products.

The authors of scientific works **[39]**, **[40]** performed a series of experimental studies on developing new recipes for meat products with improved properties due to introducing various components into their composition, particularly vegetables, fruit, and API products. According to the results of the above studies, only an organoleptic assessment was carried out, in our opinion, for such products, it is worth conducting a spectroscopic assessment and quantitative analysis of the trace element composition, taking into account the content of plant impurities, which will allow to improve the quality indicators of the finished products.

Among the sufficiently effective methods of non-destructive control, we can note the technology of hyperspectral detection of material characteristics, which is widely used in food product testing **[41]**, in particular, it expands the possibilities for improving the quality and efficiency of the production of vegetable sausages. This method makes it possible to identify the studied material's main components and predict changes in chemical and microbial indicators.

Thus, the manuscript by Mahdinia et al. **[42]** developed a model of microbial growth of cold fresh beef. Regression prediction and visualization of the structure of meat raw materials are described in detail in the manuscript **[43]** based on hyperspectral imaging to conduct a quantitative analysis of the total number of colonies in sausages.

Shi et al. **[44]** evaluated sausage quality using the hyperspectral near-infrared band, extracted characteristic bands using a continuous projection algorithm and created an effective model for characterizing and identifying sausage varieties.

Fu et al. **[45]**, using the methods of hyperspectral analysis and wavelength screening, found three undesirable plant impurities in sausage products, and developed modeling algorithms to improve the predictive performance of the constructed model.

The proposed research topic is of great importance for ensuring the quality and safety of food products. The studied methods allow the detection of the presence of various chemical elements in products and the accurate determination of their amount. Further research may contribute to improving analytical techniques, developing quality and safety standards, and formulating effective quality control strategies in the food industry. This is important from the point of view of consumer health and the competitiveness of products on the market.

The study of spectroscopic methods in combination with LIBS to assess the quality of food products is an auspicious direction. From the perspective of further research, the following directions may be engaging in this area:

Expanding the range of products examined, including different food products such as meat, fish, fruits, vegetables, grains, dairy products, etc. To get a more complete idea of the potential application of the method in various branches of the food industry.

Development of standardized methods of analysis that could be used in the food industry for quality control.

Analysis of the interaction of various chemical components in products during storage and processing will help develop optimal storage and processing conditions.

Applying machine learning and data analysis methods automates the processing of spectroscopic measurement results, quickly and efficiently analyzes large volumes of data, and identifies important dependencies between spectra and product quality indicators.

Study of the influence of various internal factors, such as humidity, temperature, pH, etc., on the spectroscopic characteristics of products. Development of portable LIBS devices that can be used at the production site or even at home for rapid analysis of product quality. Identify new spectroscopic markers of product quality that would be sensitive to certain types of contamination or degradation.

All the above-mentioned areas of research can help improve the quality and safety of food products and make the process of their control more efficient and automated.

CONCLUSION

According to the results of the evaluation of the studied product samples by laser-induced LIBS spectroscopy, the trace element composition of beef practically does not contain metals, which proves the need to introduce useful metal components into this product using the studied plant impurities. Since some of the studied samples, particularly fruits, are somewhat different from solid bodies, the noise coefficient of some spectral lines was low, and the electron temperature and electron density calculation error were relatively large. In addition, the heterogeneity of fruits increases the matrix effect. Some microelements are characterized by sufficiently low detection limits, which makes it difficult to create standard samples. Experimental lines were used in the LIBS spectra of the studied fruits, which fully satisfy the selection rules. The chosen wavelengths of 317.933 nm and 373.69 nm turned out to be quite weak, and the excitation energies of 3.15 and 3.12 eV, respectively, for the wavelengths of 393.366 nm and 396.848 nm turned out to be quite close. The projection of which is superimposed on one point. The electronic three-point fitting temperature results for banana, pineapple, and kiwi were 14507 K, 13485 K, and 12173 K, respectively.

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Contact Address:

*__Igor Palamarchuk__, National University of Life and Environmental Sciences of Ukraine, Faculty of Food Technology and Quality Control of Agricultural Products, Department of Processes and Equipment for Processing of Agricultural Production, Heroes of Defense Str., 12 B, 03040, Kyiv, Ukraine,
E-mail: vibroprocessing@gmail.com
ORCID: https://orcid.org/0000-0002-0441-6586

Fu Yuanxia, National University of Life and Environmental Sciences of Ukraine, Faculty of Food Technology and Quality Control of Agricultural Products, Department of Processes and Equipment for Processing of Agricultural Production, Heroes of Defense Str., 12 B, 03040, Kyiv, Ukraine/Bengbu University, Bengbu, 233030, Anhui, China,
E-mail: fyx@bbc.edu.cn
ORCID: https://orcid.org/0000-0002-4238-1847

Dmytro Zhuravel, Dmytro Motornyi Tavria State Agrotechnological University, Department of Technical Service and Systems in the Agro-Industrial Complex, B. Khmelnytskoho Av. 18, Melitopol, 72312, Ukraine,
E-mail: dmytro.zhuravel@tsatu.edu.ua
ORCID: https://orcid.org/0000-0002-6100-895X

Ievgenii Petrychenko, Uman National University of Horticulture, Department of Agroengineering, Institutska St., 1, 20300 Uman, Ukraine,
E-mail: 22102210g@ukr.net
ORCID: https://orcid.org/0000-0003-1037-077X

Roksolana Blishch, Lviv Polytechnic National University, Faculty name, Department of Organic Products Technology, St. George's Square, 2, 79013 Lviv, Ukraine,
E-mail: roksolanaalex1976@gmail.com
ORCID: https://orcid.org/0000-0003-1143-5264

Anatoliy Holovatyuk, Uman National University of Horticulture, Department of Agroengineering, Institutska St., 1, 20300 Uman, Ukraine,
E-mail: golowatyk@ukr.net
ORCID: https://orcid.org/0000-0002-4366-171X

Olexander Domin, National University of Life and Environmental Sciences of Ukraine, Mechanical and Technological Faculty, Department of Transport Technologies and Means of Agro-Industrial Complex, Heroes of Defense Str., 12 B, Kyiv, 03040, Ukraine,
Email: domin31@gmail.com
ORCID: https://orcid.org/0000-0002-3907-0992

Tatiana Kostiuk, National University of Life and Environmental Sciences of Ukraine, Faculty of Economics, Department of Economics, Heroiv Oborony Str.15, 03041, Kyiv, Ukraine,
E-mail: economy_chair@nubip.edu.ua
ORCID: https://orcid.org/0000-0003-1334-2731

Corresponding author: *