Chapter

Optimization of the Olive Production Chain through Optical Techniques and Development of New Cost-Effective Optical Systems Inspired by Agriculture 4.0

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Abstract

Industry 4.0 is characterized by autonomous decision-making processes, monitoring assets and processes in real time and to real-time connected networks through early involvement of stakeholders. In this scenario, there is a growing interest and a need of innovation also in the agri-food system in the production processes and quality control through the development of new interconnected sensors (IoT approach). Hardware minimization, as well as software minimization and ease of integration, is essential to obtain feasible robotic systems. A substantial change in measurement methodologies is therefore ongoing, and it is of interest the opportunity to replace the consolidated analytical techniques, based on laboratory analyses, with methods based mainly on physical approaches of rapid execution, of limited invasiveness, and with high environmental sustainability. These approaches should be applicable directly in the field or in operative environment, allowing the creation of big databases characterizing the samples, particularly large and shared through the data cloud. This chapter will aim to overview the theoretical principles of the most important technologies applied to the olive oil sector presenting some case studies and will be focused on the future perspective for all operators of the olive sector who want to use a sustainable approach and olive-growing 4.0.

Keywords: agriculture 4.0, optical analysis, Vis/NIR spectroscopy, chemometrics, sensors, qualitative parameters, green technology, machine learning, simplified system

1. Introduction

The agri-food system is increasingly showing the need to innovate production processes and the related quality controls through the use of new technologies and the use of innovative sensors that could be interconnected, approaching what is called industry 4.0. In this context, and in particular in agriculture 4.0, emerging technologies such as artificial intelligence, big data, Internet of Things (IoT) are presented as a solution to the new challenges associated with food production. It is a digitization of all agricultural systems capable of increasing yields by reducing inputs and labor requirements. Furthermore, these technologies are capable of improving the health of the environment by enabling the production of a higher amount of food on the existing land while saving further land conversions and increasing eco-efficiency [1].

Obtaining high-quality and safe agricultural and food products is now an essential condition for both producers and consumers who are more involved and interested in the various aspects concerning food production. Therefore, the agri-food industry is currently concentrating on the production of healthy products that at the same time meet the market demands, and to do this it is essential to carry out punctual and precise quality controls on the products [2].

The analytical methods currently available to assess quality require time and above all are destructive techniques or laboratory chemical analyses that also involve the use of reagents. Nondestructive techniques based on optical properties and visual evaluations of food matrices are now being used all over the world as a response to these needs.

One of the most widespread techniques is undoubtedly visible and near-infrared (vis/NIR) spectroscopy, which is based on the measurement of the variation in the spectral characteristics of a sample irradiated with electromagnetic radiation in the visible and in the near-infrared range (400–2500 nm). The variations of the spectral characteristics in a matrix can be recorded in different modalities according to the characteristics of the product but also according to the characteristics of the instruments used. Spectroscopy for analyzing agricultural and food products has proven to be an exceptional and rapid tool with little or no sample preparation [3].

This type of nondestructive technique guarantees the reduction and, in some cases, even the elimination of the use of solvents, which are instead necessary to carry out traditional chemical laboratory analyzes. Compared with vis/NIR technology, chemical techniques require a lot of time, sample preparation, and the use of chemical reagents influencing both the cost aspect and the environmental impact aspects. Moreover, in recent years, research tends to pay attention also to on/in/at-line applications, and vis/NIR spectroscopy offers several opportunities for quality control during processes: the replacement of the analytical tools and reagents related to chemical analyses with one vis/NIR spectrometer could reduce the environmental impact of analyses [4].

Vis/NIR spectroscopy is just one example of the numerous techniques that are being implemented in these fields. Paragraph 2 of the chapter will analyze the principles of the most common nondestructive techniques used in the agri-food industry, paragraph 3 will focus on the applications of these techniques in the optimization of the olive production process, and finally, fourth paragraph will illustrate the portable prototypes and future prospects of simplified optical devices.

2. Main optical nondestructive approaches and data analysis

2.1 Vis/NIR and NIR spectroscopy

Among the nondestructive techniques, spectroscopic analyses in the visible–near infrared (vis/NIR) and near infrared (NIR) regions are widely used in different fields.

Since the early 1970s, various instruments have been built that are able to exploit these technologies: instruments that acquire the sample spectrum in a specific wavelength range and record the average spectrum of a single defined area of a sample.

Vis/NIR and NIR spectroscopies are used to acquire punctual information on the nature of the functional groups present in a molecule by exploiting the interaction between light and the structure of a sample. The electromagnetic radiation is in fact able to promote vibrational transitions in the molecules. Spectra in the visible region (between 400 and 700 nm) and spectra in the near infrared region (between 700 and 2500 nm) are composed of combination and overtone bands related to absorption frequencies in the mid-infrared region (MIR, between 2500 and 50,000 nm).

All these combinations and overtone bands correspond to the frequencies of the vibrations between the bonds of the atoms that compose the molecules of the analyzed matrix. Each matrix or material is a unique seal of atoms so there are no two compounds capable of producing the same vis/NIR spectra. Through the use of chemometric statistical analyses, it is possible to use spectroscopy as an excellent tool to perform quantitative analyses. A peculiar aspect of this technique is that it does not require sample preparation, thus offering a valid alternative to traditional chemical or physical analytical methods, which instead requires time and the use of solvents or other materials. The data deriving from the spectroscopic analyses are complex and require specific statistical analyses to obtain the information of interest [5].

2.1.1 Principles and instrumentation

The chemical composition and physical characteristics of a sample determine reflection, absorption, or transmission of the electromagnetic radiation. The reflected light could cause specular reflection shine (to be avoided), while diffuse reflection is produced by rough surfaces. These reflection phenomena provide information on the sample surface. More interesting could be the scattering resulting from multiple refractions within the material. The sample heterogeneity is highly influencing the scattering effects. Also, size, shape, and microstructure of the particles have an effect on scattering.

Scattering affects the reflected spectrum, while the sample shape is more related to the absorption process. The bands of absorption in the NIR region are mainly overtones and combination bands of the fundamental absorption bands in the IR region, deriving from vibrational and/or rotational transitions. In the case of complex matrices such as foods, multiple bands and the effect of the widening of the peaks determine vis/NIR and NIR spectra with a wide coverage and few acute peaks.

To acquire a spectrum, it is necessary to use an instrument called a spectrophotometer, which consists of a light source, an accessory to present the sample, a monochromator, a detector, and optical components. Spectrophotometers are classified according to the type of monochromator: it is a device able to decompose a single polychromatic light beam into several monochromatic light beams (that contains waves of a single frequency), thus allowing to analyze the intensity as a function of wavelength.

In a filter instrument, the monochromator is a wheel holding absorption or interference filters and has a limited spectral resolution. In a scanning monochromator instrument, a grating or a prism is used to separate the individual frequencies of the radiation entering or leaving the sample so the radiation at the different wavelengths can hit the detector.

Spectrophotometers based on Fourier transform use an interferometer to generate a modulated light beam. Using the Fourier transform, the light reflected or transmitted by the sample is converted into a spectrum. The most diffused systems use the Michelson interferometer, but also polarization interferometers are employed in the optical bench of some instruments. The photodiode array (PDA) spectrophotometers have a wide diffusion; these systems are based on a fixed grating, which focuses the radiation onto a silicon array of photodiode detectors. The systems based on laser do not use monochromator but different laser sources or a tunable laser. Finally, acoustic optic tunable filter (AOTF) and liquid crystal tunable filter (LCTF) instruments are available on the market. AOTF uses a diffraction-based optical-band-pass filter easily tunable varying the frequency of an acoustic wave propagating through an anisotropic crystal medium. LCTF instruments use a filter to create interference in phase between the ordinary and extraordinary light rays passing through a liquid crystal. The combination of different tunable stages in series can result in a high resolution.

2.2 Computer vision and image analysis

One of the limitations of spectroscopic analyses is the punctual measurement and therefore the inability to provide information on the distribution of an object. Depending on the uniformity of the qualitative attribute to measure, it may be necessary to repeat the spectral acquisition in several points on the sample.

In order to get the spatial distribution, vision technique is a solution. With the huge development of imaging technology, computer vision results attracting for agri-food industry. A large number of applications have been developed for quality inspection, classification, and evaluation of agri-food products [6, 7]. Image data can reflect many external features of a sample such as color, shape, size, surface defects, or contaminations. Computer vision has been applied to solve various food engineering problems ranging from quality evaluation of foodstuffs to quality attributes unavailable to human evaluators.

Computer vision tools are powerful but not much useful for in-depth investigation of internal characteristics. This is due to the very limited capability to provide spectral information with this technique.

2.2.1 Multispectral and hyperspectral images

RGB images, represented by three overlapping monochrome images, are the simplest example of multichannel images. The multispectral images are usually acquired in three/ten spectral bands including in the range of visible, but also in the range of infrared, fairly spaced. In this way it is possible to extract a larger amount of information from the images respect to those normally obtained from the RGB image analysis. The bands that are used in this analysis are the band of blue (430–490 nm), the band of green (491–560 nm), the band of red (620–700 nm), and the band of NIR and MIR. Different spectral combinations can be used depending on the research aims. The combination of NIR-R-G (near infrared, red, green) is often used to identify green areas, for example, from satellite images. On the contrary, the combined use of NIR-R-B (near infrared, red, blue) is very useful to analyze fruit ripeness, thanks to chlorophyll absorption in the red range. Finally, the combination of NIR-MIR-blue (NIR, MIR, and blue) could be used to observe the sea and ocean depth.

Hyperspectral imaging (HSI) is a powerful tool combining spectroscopy and imaging into a three-dimensional data structure (hypercube). The HSI is based on the acquisition of a large number of images at different spectral bands, allowing analysis of each pixel obtaining at the same time a spectrum associated with it. The data structure of a hyperspectral image is data cube, considering two spatial directions and one spectral dimension.

Hyperspectral technology can integrate the advantages of conventional digital imaging and spectroscopy to obtain both spatial and spectral information from an object simultaneously.

In recent years, HSI has been applied to food safety and quality detection, because the technology can achieve rapid and nondestructive detection of food, and the requirement to experimental condition is low [8].

HSI has opened up new possibilities within agri-food analysis, in particular Liu et al. [9] outlined detailed applications in various food processes including cooking, drying, chilling, freezing and storage, and salt curing, emphasizing the ability of HSI technique to detect internal and external quality parameters in different food processes [9].

Using HSI, the hypercube can be acquired in reflectance, transmission, and fluorescence. Nevertheless, the most used acquisition techniques for spectral images are reflectance, transmission, and emission, considering the scientific works published. HSI has many advantages, e.g., the huge time savings that can be obtained for the application to industrial production processes. The advantages of HSI for the agri-food sector can be listed as follows: (i) not necessary sample preparation; (ii) noninvasive methodology that avoids sample losses; (iii) economic value related to time, labor, reagents, savings, and a strong cost-saving for waste treatment; (iv) for each pixel of the sample is acquired the full spectrum and not only few wavelengths; (v) many constituents can be predicted at the same time simultaneously; (vi) special region of interest could be selected and analyzed.

The hypercube generated by using HSI provides a large dataset. The information derived from the hypercube may contain also redundant information. This data abundance may cause a high computational load due also to the long acquisition time. Therefore, it is desirable to reduce this load at acceptable levels, considering the application of HSI for real-time application. For this purpose, the spectral image is appropriately reduced using chemometric data processing, mainly selecting the most informative wavelengths. Using the selected spectral bands, a multispectral system can be envisaged for application at industrial level.

2.3 Chemometrics in agri-food sector

Chemometrics is defined as a branch of chemistry that studies the application of mathematical or statistical methods to chemical data. The International Chemometrics Society (ICS) defines it as a chemical discipline that uses mathematical and statistical methods to: design/select optimal procedures and experiments, provide maximum chemical information by analyzing data, give a graphical representation of this information, in other words, information aspects of chemistry. Chemometrics is essential for processing multivariate data obtained by optical techniques and for obtaining useful information for solving problems related to spectral noise.

One of the most used techniques is the Principal Component Analysis (PCA), also known as the Karhunen-Loève transform. It is an unsupervised exploratory qualitative analysis technique that allows reducing the more or less high number of variables describing a set of data to a smaller number of latent variables, limiting the loss of information.

Other chemometric techniques used extensively in these fields are supervised techniques, techniques that require method validation and that are used to obtain the quantitative prediction of the parameters of interest. Among these we find regression techniques such as Partial Least Square (PLS) regression or Multiple Linear Regression (MLR). The models developed using these techniques must then be tested using independent samples as validation sets to verify the accuracy and robustness of the model.

3. Application of nondestructive techniques for the optimization of the olive production process and enhancement of by-products

Agricultural products are converted into food products by using different processes. The process to achieve the best performance is carried out considering both efficiency and the target quality of the final food product, in order to be competitive on the market. The production of a high-quality extra virgin olive oil (EVOO) could be reached considering an optimization of the different production steps: olive harvesting and handling; milling operation to be done in a short time after harvesting; use of a modern milling plant equipped with suitable technologies to control process conditions. A high level of control of the standard operating conditions is a crucial aspect to avoid process failures and to maintain the highest final product's quality.

During the ripening process, the olives undergo the variation of various physical parameters such as weight, color, pulp-to-stone ratio, and texture and also of chemical parameters such as oil content, fatty acid composition and polyphenol, tocopherols, and sterols content. These characteristics are of great importance because they influence the quality, the yield, and the shelf-life of olive oil and of the by-products of olive production. Olive oils deriving from overripe fruits, for example, have a reduced shelf-life due to the increase in polyunsaturated fatty acids and the decrease in the total content of polyphenols. In particular, in the olive oil extraction chain, process control and management determine the conditions for producing high-quality oil, which is essential both to maintain consumer confidence and to evaluate potential plant yield losses. The flow sheet of the process is based on the following steps: olive cleaning, crushing to obtain a paste, paste malaxation, solid liquid separation, and liquids separation. Solid–liquid separation is a crucial aspect of the entire process. It is based on the separation of the solids (called pomace) from the other components, namely oil and wastewater.

It is important to have online information on the oil content of the olives to set corrective actions during the process in order to reach the best extraction performance. Nowadays the consolidated analysis protocol is based on the Soxhlet method to analyze the oil content in olives, pomace, and pate. This protocol requires a time-consuming drying step, followed by an extraction based on the use of solvent.

For this issue, the Soxhlet method is often substituted in routine analyses by Nuclear Magnetic Resonance (NMR) spectroscopy. Also, this procedure is not sufficiently fast due to water interference (the olive pomace must be completely dry). Consequently, this method is unsuitable for an online application.

A precise monitoring of the intermediate products between the olives entering and the oil outlet (the paste, the pomace, and the pate) is crucial for control of the process progress. It is useful to establish correlations among olives, paste, pomace, patè, and oil. For this aim, rapid and possibly easy-to-use technologies are required to assess olive ripening and the characteristics of the by-products. In this way an early detection of possible failures and a continuous monitoring of the production process during its crucial steps result in an adequate control of the oil quality and yield. From this point of view, nondestructive optical applications could greatly help the sector.

Several studies have highlighted the enormous opportunities offered by NIR spectroscopy in terms of applications for quality control during the process, performing on/in/at-line measurements on olive fruits, on pastes, and on oils [10]. Researchers tend to focus attention on the online applications of noninvasive technologies in order to reduce the gap between laboratory scale experimentation and the olive milling industry [11]. A number of studies applying different vibrational techniques in the olive oil chain can be found in the literature, mainly with the aim of standardizing the procedure for an application as official control of the end product [12]. For this purpose, it is crucial to evaluate the optimal spectral range to be used, and the chemometric methods to be performed to obtain robust predictive models for the estimated parameters. On intact olives, Beghi et al. [13] studied the capability of portable vis/NIR and NIR spectrophotometers to investigate different texture indices for the characterization of olive fruits entering the milling process. Salguero-Chaparro et al. [14] used NIR spectroscopy for the online determination of the oil content, moisture, and free acidity performing measurements directly on intact olives.

NIR was used for the analysis of olive by-products (e.g., olive pomace) performing research studies both in lab-scale and in processing mill lines. Barros et al. [15] applied FT-NIR spectrometry (1000–2500 nm) in combination with partial least squares regression for direct, reagent-free determination of fat and moisture content in milled olives and olive pomace; while Allouche et al. [16] used an optical NIR sensor coupled with artificial neural network for online characterization of oil and virgin olive oil to optimize the process. Finally, Giovenzana et al. [17] verified whether vis/NIR spectroscopy could be used to predict the oil content of intact olives entering the mill and of olive paste, pomace, and paté during the milling process.

Multispectral and hyperspectral systems were applied for monitoring the ripening process [18, 19] or on olive oil samples to estimate acidity, moisture, and peroxides by using online system [20] or to discriminate flavored olive oil [21]

4. Portable prototypes and future perspectives toward simplified systems

Having demonstrated the effectiveness of nondestructive analyzes, some problematics remain related to the costs and the dimensions of the instrumentation, two factors that prevent or severely limit some applications of these tools. Research and innovations are allowing these devices to reduce size and weight: devices tend to be more compact and portable. In order to support small producers, systems that are at the same time simple to use and that have a low cost are desirable, so as to make these technologies usable to all and allow real-time evaluations of qualitative and quantitative parameters [22].

Nowadays, chapter authors are working on designing and developing of a simplified LED device for intact olives quality evaluation. A first version of a fully integrated, LED prototype was built and now results patent pending (**Figure 1**).

The peculiar sensory and nutritional characteristics of olive fruits have led to a sharp boost of the demand for the main derivative products in traditional producing areas and elsewhere in the world. Several destructive, expensive, time-consuming, and not sustainable techniques have been used to assess the degree of olives ripeness. To at least partially replace these types of analyses, in 1975, a Maturity Index (MI)

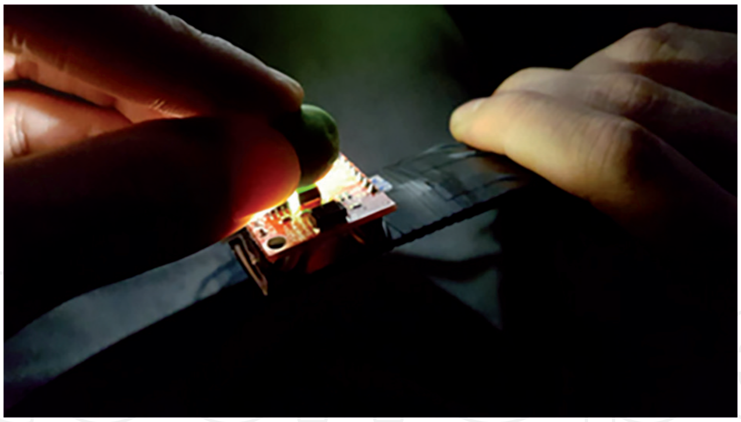

Figure 1.
First version of a simplified LED prototype during optical acquisitions on olives.

was been proposed by Uceda and Frias. This methodology is based on an inexpensive and easy destructive procedure for a visual determination of the best harvesting time. The method is based on color changes of olive skin and flesh; the protocol foresees to classify 100 olives into eight groups, from intense green (category 0) to black with 100% purple flesh (category 7). Despite this protocol being largely used, MI is highly dependent to the operator experience and could be affected by human error. Moreover, olives color changes are very different among cultivars and during the ripeness evolution.

The aim of this research was to design, build, and test cost-effective and user-friendly devices able to optically predict the olive oil and moisture content in olive fruits in order to support small-scale growers in planning the optimal harvest date.

The prototype device is composed of tuned photodiode arrays, interference filters, LEDs, optics and incorporates MEMS (microelectromechanical systems) sensors for spectral measurement in the visible (vis) and short-wave near-infrared (SW-NIR) region.

Therefore, the vision on the application of this sensor can solve several problems in the field of olive growing. Firstly, it can objectify the evaluation of the quality of the olives in the field (to identify the ideal moment of harvesting) and before the milling process to define the correct price of the olives. Secondly, the logistics inside the mill is not easy to be managed. For instance, a preventive evaluation of the maturation parameters could avoid prolonged stop of olives bins in the receiving areas, which causes the deterioration of the product. Finally, the LED prototype could address to olives classification, in terms of qualitative attributes (**Figure 2**), which is useful for high-added-value olive oil productions.

This new generation of optical devices could be a starting point to build a new concept of cost-effective sensors. The stand-alone instrument should be able to acquire and predict the most important ripening parameters directly from measurements in field. This approach could allow olive maturation monitoring bringing the laboratory directly into the field without picking the olive and reducing sampling waste.

The integration of simple multivariate models in the microcontroller software would be easy calculate and visualize the real-time values of the predicted parameters directly on the device to support operators decision-making with objective numbers.

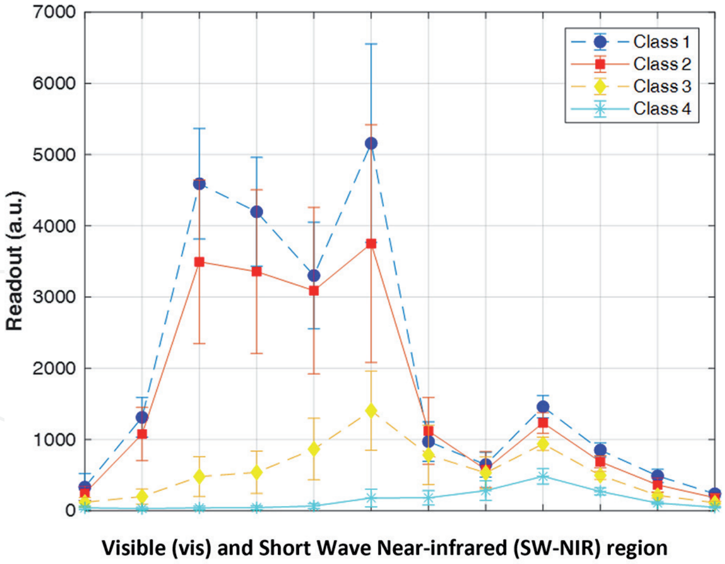

Figure 2.
Average optical readouts and relative standard deviations from each olive ripening class.

5. Conclusions

Among the different available techniques, vis/NIR and NIR spectroscopy and hyperspectral imaging are valid tools for monitoring of qualitative parameters and for maturation control in olive oil sector. The optical instruments currently on the market are mainly laboratory instruments with dimensions and costs that are not suitable for use in real pre- and post-harvest applications, in particular for SME. To overcome this problem, research has concentrated in recent years on feasibility studies and simulations of simplified systems. These studies have been focused on the preliminary design of systems dedicated to single types of product, aiming at a reduced size and low cost.

At the same time, the development and diffusion of cost-effective and increasingly high-performance hardware have opened up new research opportunities envisaging new systems to support optical measurement for the control and management of the pre- and post-harvest processes.

Therefore, further studies both for model improvement and for the design of the system are needed. In a view of olive-growing 4.0, a similar tool based, for example, on a prototype using specific LED for the illumination will lead to quick and accurate analyses in order to get a useful monitoring of the ripening process. In this way it will be possible to estimate the best harvest period and to provide objective features to the operators in terms of quality attributes.

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