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Exploring the evolution of olive-fruit electric capacitance during maturation as an indicator of oil content accumulation

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Abstract

Olive oil is a highly appreciated food product due to its outstanding nutritional profile. Because of the huge current and expected increasing demand, the olive sector is undergoing a transition to more productive approaches. In this respect, precision farming is increasingly playing an outstanding role aimed at yielding novel accurate spatial and temporal information in a variety of factors involved in olive growing and subsequent product transformation. In this context, this study explores the hypothesis that chemical transformations undergone by olive fruits during their maturation impact on their capability to store electric charge. Concretely, this work tries to elucidate how the electric capacitance of fruits is affected as oil content increases. The results obtained encourages to continue with further investigation, this with the final goal of developing specific devices, usable directly in the field, to characterise olive ripening in an easier and more cost-effective manner compared to traditional chemical methods.

Keywords: Bioresponses, Biosensors in agriculture, Crop processes, Decision support systems, Grading systems and quality assessment, Precision agriculture.

Exploración de la evolución de la capacitancia eléctrica de las aceitunas durante la maduración como indicador de la acumulación de contenido graso

Resumen

El aceite de oliva es un producto alimenticio muy apreciado debido a su excelente perfil nutricional. Debido a la enorme demanda actual y prevista, el sector olivarero está experimentando una transición hacia enfoques más productivos. En este sentido, la agricultura de precisión está jugando un papel cada vez más destacado en la obtención de nueva información espacio-temporal precisa sobre una variedad de factores relacionados con el cultivo de la aceituna y la posterior transformación de esta. En este contexto, este estudio explora la hipótesis de que las transformaciones químicas que sufren las aceitunas durante su maduración impactan en su capacidad para almacenar carga eléctrica. Concretamente, este trabajo trata de dilucidar cómo se ve afectada la capacitancia eléctrica de los frutos a medida que aumenta su contenido graso. Los resultados obtenidos apuntan en la dirección de continuar con la investigación, con el objetivo final de desarrollar dispositivos específicos, utilizables directamente en campo, para la caracterización de la maduración de la aceituna de una manera más fácil y rentable en comparación con los métodos químicos tradicionales.

Palabras clave: Biorespuestas, Biosensores en agricultura, Procesos agrícolas, Sistemas de soporte a la decisión, Sistemas de clasificación y evaluación de la calidad, Agricultura de precisión.

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1. Introduction

The olive crop is crucial for the agricultural sector of many countries in the Mediterranean basin. Olive oil, the primary by-product of the olive sector, is increasingly regarded by consumers as a vital ingredient for a healthy diet due to its richness in valuable nutrients and bioactive compounds with therapeutic benefits (Ghanbari, Anwar, Alkharfy, Gilani, & Saari, 2012). In recent campaigns, the European Union (EU) accounts for approximately 70% of global olive oil production. Within the EU, Spain and Italy alone contribute around 80% of that total. This data exemplifies the importance of the olive sector as a crucial driver of socio-economic development in the countries of the Mediterranean basin, especially in Spain.

In recent decades, the olive sector has undergone a transformation from traditional cultivation systems to new crop models, with the most popular being the super high-density (SHD) olive orchard. This cultivation system features high plant density. Trees are arranged in rectangular layouts with spacing between 1-1.5 meters within rows and 3-3.5 meters between rows. They are trained to form continuous hedgerows, resulting in a two-dimensional tree shape. This crop configuration maximises the productivity of the land unit due to the high fruit yields obtained by individual trees compared to traditional olive trees. Furthermore, the features of this cultivation pattern facilitate mechanisation of cultural practices, resulting in greater crop profitability (Barranco Navero, Diego, Fernandez Escobar, Ricardo, Rallo Romero, 2017). However, this cultivation system still has aspects susceptible to improvement, such as the management of agricultural inputs. In this sense, precision farming strategies are gaining interest among the research community.

Precision farming is a management approach designed to assess spatial and temporal variations within an agroecosystem and apply location-specific treatments through the utilization of diverse technologies and methodologies (Fountas, Aggelopoulou, & Gemtos, 2015). The variability within a crop is influenced by spatial and temporal variations in factors such as soil quality, partial incidence of plant diseases, exposure to solar radiation or water sources, climate conditions, etc. Thus, unlike the traditional paradigm of agronomic management, which relies on homogeneous resource use, precision farming aims to allocate them to plants according to their specific needs in a segmented manner. One area of focus for precision farming in the context of oliviculture is the monitoring of the olive fruit ripening process.

The olive ripening process begins after a period of 25 weeks of fruit growth. During this time, the fruit develops to its final size while retaining its original green skin colour. Subsequently, chlorophyll pigments in the olive skin are progressively replaced by anthocyanins, resulting in the characteristic purple coloration. This change in appearance is also reflected in the chemical composition of the fruits. Specifically, there is an accumulation of fatty acids, primarily oleic acid, which contributes to the acidity of the oil. At a certain point, lipogenesis ceases, marking a milestone that represents the peak in the quality status of olive fruits, thereby indicating the optimal harvest time objectively. The ripening process can evolve at a diverse pace in different areas of a field. This variability can be compensated for through cultural practices. Therefore, having technological resources that allow for monitoring olive quality with high spatio-temporal resolution would enhance crop management. On one hand, it would enable site-specific treatments to address heterogeneity during growth and early ripening phases. On the other hand, growers could decide on the moment of harvest based on objective parameters, providing the opportunity to devise harvest strategies aimed at diversifying production.

One of the main parameters used to assess olive quality is the oil content. Traditionally, this parameter has been determined by chemical methods such as Soxhlet digestion or nuclear magnetic resonance (NMR). These techniques are expensive as they require specific laboratory facilities and expert personnel. These limitations restrict the potential of these methodologies to achieve ripening monitoring with a high spatio-temporal resolution. This normally leads growers to conduct homogeneous harvesting based on subjective criteria such as intuition and visual decisions.

The application of precision farming techniques to ripening control entails the development of new resources that allow for precise monitoring of ripening parameters at an affordable cost. In this sense, diverse technologies have been proposed by the research community. Image sensors are very popular, with numerous works based in different vision technologies (Bellincontro et al., 2012; Butz, Hofmann, & Tauscher, 2005; Cayuela & Camino, 2010; Guzmán, Baeten, Pierna, & García-Mesa, 2012; Kavdir, Buyukcan, Lu, Kocabiyik, & Seker, 2009; Noguera, Millan, Aquino, & Andújar, 2022; Salguero-Chaparro, Baeten, Fernández-Pierna, & Peña-Rodríguez, 2013).

In this work, an alternative approach is proposed based on the electrical behaviour of the fruits. The initial hypothesis is that the chemical modifications undergone by fruits as a consequence of maturation have an impact on their capability to store electric charge. Previous research has reported that measurements of the electrical properties of fruits correlate with quality parameters of different crops. In this sense, studies based on electrical impedance have shown that this electrical property is related to the physiological changes undergone during maturation by nectarines (Harker & Maindonald, 1994), persimmon (Harker & Forbes, 1997), tomato (Varlan & Sansen, 1996), and mango (Rehman, Abu Izneid, Abdullah, & Arshad, 2011). The present study aims to extend this research to olive fruits. Specifically, this work aims to elucidate how the capacitance of olive fruits is affected as oil content increases during maturation. Satisfactory results will incentivise future research to develop a specific prototype specially designed to operate under field conditions. It would serve as an objective tool to characterise olive ripening in an easier and more cost-effective manner compared to traditional chemical methods.

2. Materials and methods

To elucidate the initial hypothesis posed in this research, it was necessary to gather a comprehensive data set of capacitance measurements of olives with a wide range of oil content. To achieve this, a commercial olive crop was monitored throughout a full ripening season. The following subsections address the specific details of the conducted experiment.

2.1. Study site description, and experimental field protocol design

The study site was a commercial olive orchard (*Olea europaea*, cv. Picual), provided by Nuestra Señora de la Oliva, S.C.A., located in the province of Huelva, Spain (37°20'28.96'' N and 7°01'54.98'' W). The plant spacing pattern in this field corresponds to a traditional olive orchard, with trees arranged in squares (7x7 m) and trained to form globe shapes. This field has a drip irrigation system to apply localised irrigation during the summer drought period. Fertilisation is applied alongside the irrigation water, with nutrient rates adjusted according to the phenological phase of the annual cycle and based on periodic foliar analysis.

For this experiment, an experimental plot of one hectare was delineated. This delineation ensured that the olive trees included in the experiment were exposed to homogeneous agronomic conditions. This approach aimed to avoid the effect of natural variations in the field on the maturation pace of the sampled trees, making the normal evolution of the fruits during the ripening process the sole source of variability regarding ripening indicators. This approach aims to gather a dataset of OCDM with a homogeneous distribution.

During an entire ripening campaign, weekly samples were collected. The first sample collection took place after the post-summer fruit growth phase in September, and it was repeated weekly until harvest in November. Thus, six sampling campaigns were conducted, collecting 15 olive samples in each campaign, thus resulting in a total of 90 samples. Each sample unit consisted of approximately 200 g of olives collected from the same branch of a randomly selected tree. After being picked, the samples were packaged, labelled, and refrigerated for transport to the laboratory for subsequent analysis.

2.2. Capacitance measurements

Capacitance measurements were performed in laboratory using a digital LCR meter (U1731C, Agilent Technologies, California, EEUU) coupled to a metallic probe (Figure 1). This device was used in capacitance mode, and measurements were performed at 100 Hz frequency.

Figure 1. Digital LCR meter coupled with the metallic probe.

The measurement process followed the protocol below. The samples were kept refrigerated to maintain a constant temperature and were taken from the refrigerator just before measurement. Subsamples of 25 olive fruits were randomly selected from each olive sample (200 g). Each olive fruit was individually measured with the LCR meter in capacitance mode. The measuring process involved penetrating the olive epicarp with the metallic probe of the device, inserting it until reaching the olive mesocarp. The capacitance data was then recorded, and the fruit was removed from the system. The average capacitance measured from the 25 individuals was registered as representative of the whole sample. Between measurements, the metallic probe was cleaned with paper. After measuring the 25 fruits corresponding to an individual sample, the measured olives were repackaged with the rest of the sample and refrigerated. All the samples collected in a single sampling event were measured on the same morning they were collected. Subsequently, they were sent to an external laboratory to assess reference quality parameters using standard chemical methods.

2.3. Reference analysis

In this study, oil content per dry matter (OCDM) was used as ripening indicator, as it is widely used by the olive industry to decide the optimal time for harvesting. The reference analysis of this parameter was conducted in the laboratory, in accordance with the official methodology. To determine the OCDM of a sample, the moisture (M) and the oil content per fresh weight (OCFW) must first be obtained. The determination of M was carried out through the drying method in an oven at 105 °C (ISO662:2016). According to this method, a 25 g portion of the sample is placed in a porcelain capsule and dried in the oven at 105 °C for 6 h. Then, the sample is cooled in a desiccator, weighed, and returned to the oven, repeating these operations until, between two consecutive weightings, the variation in weight loss is less than 0,02 g. At this point, the difference between the initial and final weight is considered as the M content of the sample. Reference analysis of OCFW was undergone by using the Soxhlet methodology (UNE 55030:1961). This method involves introducing the dried sample, used for M determination, into a Soxhlet extractor, where fat is extracted by exposing the sample to n-hexane for 4 h. Then, the sample is placed into the oven again at 105 °C to remove the traces of solvents. The amount of oil recovered is used to determine the OCFW and, from this measure, the OCDM is calculated according to the following equation:

$$\text{OCDM} = \frac{\text{OCFW}}{100 - \text{M}} \tag{1}$$

2.4. Methodology for estimation model development

The objective of this research was to elucidate the correlation between the capacitance of olive fruit and its OCDM, with the aim of using capacitance as an input variable to estimate OCDM. Given the univariate nature of this approach, a linear regression model was initially developed. Additionally, two polynomial models of second and third degree were evaluated.

To develop and test the models, the complete dataset (n = 90) was randomly divided into two subgroups: 70% for training and 30% for external validation (test). The training group was then used to calibrate the models, while the external validation group was kept unused during model training and employed solely for subsequent model evaluation.

2.5. Methodology for estimation model evaluation

The goodness of olive OCDM characterisation by means of their electric capacitance was assessed by the coefficient of determination (R^2) and the root mean square error (RMSE). These metrics were calculated by comparing the actual OCDM values obtained from standard chemical methods with the values estimated by the developed models. Lower RMSE and higher R^2 indicate better model performance.

The root-mean-square-error, $RMSE$, was calculated as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\hat{y}_i - y_i)^2}{n}} \qquad (2)$$

where y_i and $\hat{y}_i$ are the actual and estimated fat content for the i-th sample of the external validation group.

3. Results and discussion

Figure 2 shows the OCDM values obtained by chemical methods for the 90 olive samples. The samples are ordered by collection date, with each group of 15 samples representing one week of collection. A gradual increase in OCDM is evident as maturation progresses throughout the weekly sampling events.

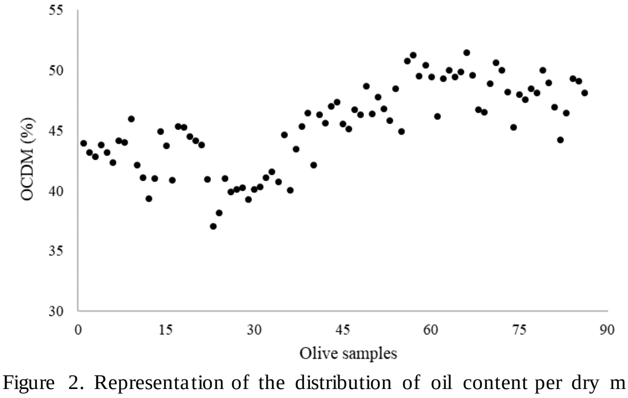

Figure 2. Representation of the distribution of oil content per dry matter (OCDM) values per sample in the study set (n=90). Samples organized in order of collection (15 samples per week).

Figure 3 shows the mean capacitance values for the 90 olive samples. The samples are also arranged in collection order, revealing a gradual increase in capacitance as maturation progresses. This trend mirrors the evolution of OCDM. The standard deviation of the samples increases as maturation progresses, indicating greater variation in the later samples. This increased variation might be explained by unequal ripening paces among the fruits within a sample.

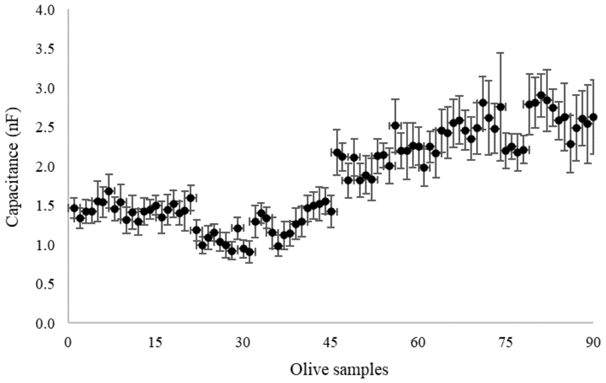

Figure 3. Representation of the mean capacitance value per sample in the study set (n=90). The vertical bars represent the standard deviation inside each sample unit (25 olive fruits).

To investigate the relationship between olive fruit capacitance and OCDM, several estimation models were evaluated. Given the focus on a single variable (univariate nature), a linear regression model was first tested. Subsequently, second-degree and third-degree polynomial models were assessed to determine if non-linear models provided a better fit for the relationship between the variables. The fitted models following the training phase are presented graphically in Figure 4. The models were evaluated using an external dataset reserved for testing, unused during the training phase. The mean capacitance of each sample served as input to predict olive OCDM using the linear, second-degree polynomial, and third-degree polynomial models. Figure 5 presents a correlation analysis between the reference OCDM values (obtained by standard chemical methods) and the estimated values from each model (Figures 5a-c) applied to the test dataset. Table 1 summarizes the performance metrics (R^2 and RMSE) calculated for these models. The linear model explained 76% of the variance in the test dataset, indicating a linear trend between olive fruit capacitance and OCDM. However, the second-degree polynomial model achieved superior performance, explaining 80% of the variance. The third-degree polynomial model also outperformed the linear model but exhibited slightly lower explanatory power compared to the second-degree model. These findings were corroborated by the RMSE values obtained from each model's estimations (Table 1).

Table 1. Coefficient of determination (R^2) and root-mean-square error (RMSE) between OCDM measured by chemical methods and those estimated values based on linear, second-degree polynomial, and third-degree polynomial models. These metrics were derived from the test dataset

	R^2	RMSE
Lineal	0.76	1.47
Polynomial grade 2	0.80	1.42
Polynomial grade 3	0.78	1.46

Our findings demonstrate a clear correlation between olive fruit capacitance and OCDM. While the linear model explained a significant portion of the OCDM variance, the underlying relationship between the dependent and independent variables exhibited a non-linear trend. This non-linearity was effectively captured by a second-degree

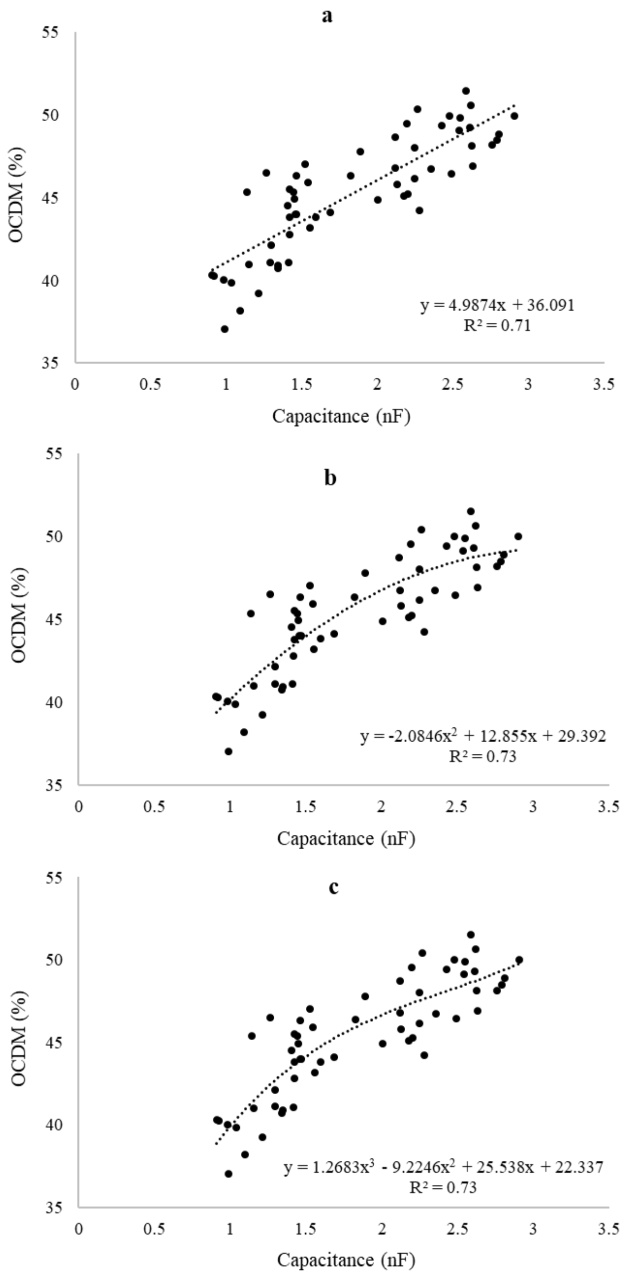

Figure 4. Linear regression model (a), second-degree polynomial model (b), and third-degree polynomial model (c) based on the OCDM measured by chemical methods and the mean capacitance of the training set samples.

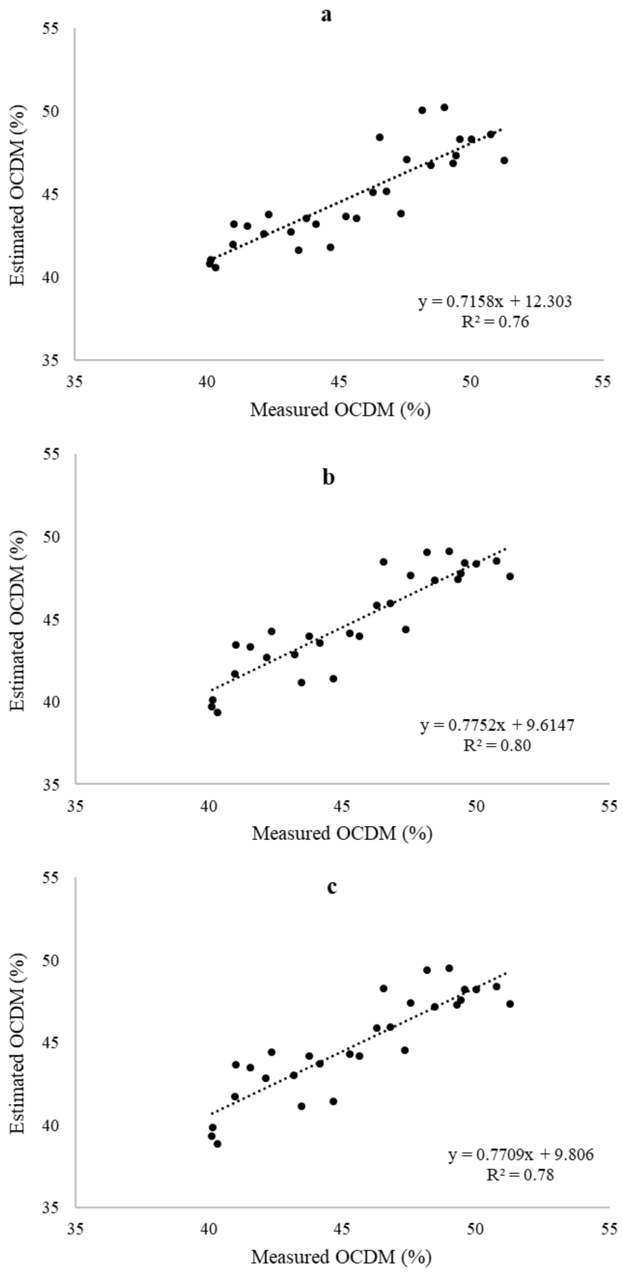

Figure 5. Correlation analysis between OCDM values measured by chemical methods and those estimated by the linear (a), second-degree polynomial (b), and third-degree polynomial (c) models in the test dataset.

polynomial model. However, Figure 4 reveals some deviations from the fitted lines in the data distribution, as evidenced by the scatter of data points. This fact might be due to a non-optimal statistical representativity of the average capacity measured from 25 olives, randomly selected from the whole population of 200 g chemically analysed. This assumption is supported by the high standard deviation of the capacitance of olive fruits at advanced maturation stages (Figure 3). Indeed, every population of 200 g ($n = 90$), is composed of olive fruits being at the same phenological stage, which is exclusively determined by visual features. However, when olive fruits reach their final size and green colour, there is still a wide margin for they to accumulate oil, which inevitably leads to population heterogeneity, even within the same tree. Future investigations will focus on designing a strategy to overcome this limitation.

The results provided in this research demonstrate a clear relationship between the electrical capacitance of olive fruits and their OCDM. These results are promising for the development of an olive fruit ripening appraisal system. Compared to other methodologies proposed at the research level, such as image-based spectroscopy (Stella et al., 2015), this approach would offer several advantages. One of then lies on its cost-effectiveness, an LCR meter (a device measuring inductance, capacitance, and resistance) is significantly cheaper than spectral systems. Furthermore, the proposed capacitance-based method offers greater ease of use for personnel in field settings compared to spectral equipment, which necessitates a certain level of expertise for operation. These advantages ensure the accessibility of the methodology for small to large-scale olive farmers. A potential limitation of the proposed method is that it requires a small sample from the fruit. However, the damage caused is minimal and does not affect the fruit's suitability for processing.

The possibility of direct assessment by field personnel would offer a precise view of the olive fruit maturation process. This would empower growers to implement precision farming techniques, enabling them to address variability in fruit ripening within their crops and adjust harvest timing accordingly. This targeted approach would facilitate the diversification of olive oil production to achieve fruits with desired characteristics, such as high oil content, ultimately enhancing the added value of olive oils in the sector.

4. Conclusion

This paper presents the exploration of the hypothesis that electric capacitance of olive fruits evolves as maturation does. To this end, 90 olive fruit samples were collected during an olive season, and their oil content per dry matter (OCDM) was determined by means of reference chemical analysis. In parallel, the samples were also electrically characterised in terms of capacitance by using a digital LCR meter. To investigate the correlation between olive fruit capacitance and OCDM, linear, second-degree polynomial, and third-degree polynomial models were trained to predict OCDM using capacitance as input. These models were subsequently evaluated using external validation. All evaluated models achieved satisfactory performance; however, the second-degree polynomial model yielded the best results. Notwithstanding, the authors hypothesises that inherent inner-sample variability may have prevented to find even higher results, so strategies will be designed to deal with this limitation in future experiments.

At the light of the results of the presented study, the authors consider the existence of strong evidence that validates the formulated hypothesis, indicating that electrical capacitance is a promising indicator of olive fruits OCDM. Therefore, this work encourages further research with the goal of developing a dedicated device for the direct and field-based assessment of olive ripening. This novel approach has the potential to serve as a more affordable and efficient alternative to traditional chemical methods.

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