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Innovative Sensor Technologies for Agrifood Quality Assessment

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Summary:
In the agrifood sector, ensuring product quality and authenticity is critical for both producers and consumers. Optical sensor technologies, such as fluorescence and Raman spectroscopy, integrated with machine learning, enabling rapid, non-invasive, and cost-effective analysis and have still a large potential for real-time monitoring of agrifood products. Particularly for portable sensing devices, data-driven prediction models can improve transparency and sustainability in the agrifood supply chain. An example is the quality determination of extra virgin olive oil and wine.

Keywords: Fluorescence spectroscopy, deep learning, food quality, machine learning, olive oil

Introduction

Optical sensing offers rapid, non-invasive, and cost-effective analysis, enabling real-time monitoring of complex systems with minimal sample preparation. To develop affordable, portable, and precise sensors, hardware capabilities must remain constrained, making innovation in software, particularly using machine learning and deep learning (DL), a crucial enabler for applications such as chemical and biological analysis.

DL has shown significant potential in spectroscopy, as it can increase both the quality of information, by learning to extract physico-chemical signatures from noise, and the quantity of information through the automated extraction of relevant spectral features.

Advanced quality control techniques for agrifood products, powered by DL and optical sensing, are crucial to address increasing global demands, resource constraints, and the reduction of waste throughout the production process.

Current Challenges

Deep learning offers significant potential in spectroscopy but faces several key challenges. The first issue is the data availability: spectroscopy datasets are often small, heterogeneous, and expensive to acquire, limiting model training and generalization capability. A second issue is the lack of transparency on how a DL model learns during the training (functioning as black box), making it difficult to interpret predictions and reducing the trust in critical applications such as food quality. Furthermore, standard DL architectures are not optimized for high-dimensional, correlated spectral data, in contrast to other fields of application such as computer vision. Finally, begin DL computationally hungry, is not suited for deployment on real-time and field-ready devices.

Application to Olive Oil

quality control of extra virgin olive oil (EVOO) is an example of challenging use-case. EVOO is a high-quality product that is widely consumed for its health benefits and culinary properties. However, both during production process and storage, its quality continuously deteriorates due to oxidation processes. It is impossible for producers to determine olive oil quality during the oil lifecycle effectively and frequently enough.

This issue can be solved using a simple minimalistic low-cost sensor to overcome the limitations of traditional methods for evaluating olive oil quality, that are expensive and time-consuming, requiring multiple chemical analyses. The schema and photo of such a device are shown in Fig. 1.

Such portable device requires advanced software to extract efficiently quality indicators of olive oil. By using one-dimensional convolutional neural networks (1D-CNNs) it is possible to extract key physicochemical parameters, such as acidity, peroxide value, and UV spectroscopic indices, from a single fluorescence spectrum without any pre-processing (Fig. 2) [1].

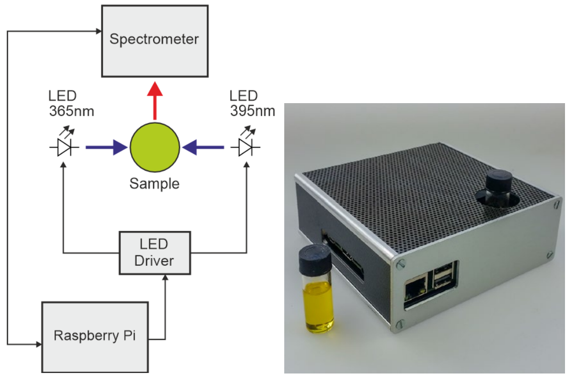

Fig. 1. Schematics (left) and photo (right) of the minimalist fluorescence sensor. Blue: Excitation light, red: Fluorescence.

While the results are promising, the small dataset and limited diversity in oil samples indicate the need for further studies with larger and more varied datasets.

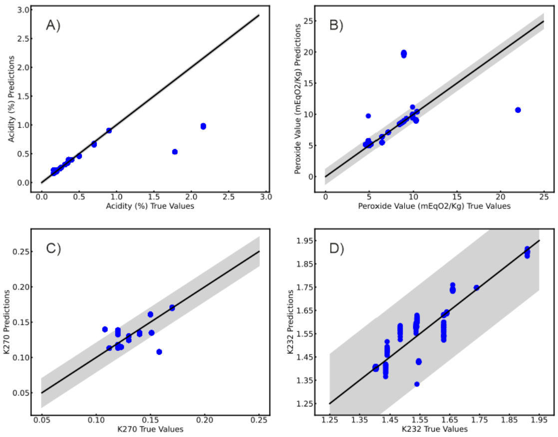

Fig. 2. Comparison of the predicted and measured (true) of the quality indicators parameters: A) acidity, B) peroxide value, C) K270 and D) K232. The solid line corresponds to predictions equal to the true labels. The grey area illustrates the experimental error on the true values. (Taken and adapted from [1]).

An approach to overcome the limitation of sparse or scares datasets is to train models on synthetic data or other type of data and exploit transfer learning to adapt it to the spectral data (e.g. fluorescence spectra) [2]. Additionally, using multi-dimensional data, in particular excitation-emission matrices (EEM, Fig. 3, top panel), it is possible to obtain detailed insights into the absorption and emission characteristics of substances, thereby acting as an effective fingerprinting tool. Furthermore, the fusion of deep learning and domain adaptation allows understanding and predicting the oxidation state of extra virgin olive oil with a high accuracy. By using a pretrained MobileNetv2 neural network model, trained on a large dataset of photographical images, and fine-tuning it for spectroscopic data, it is possible to effectively predict quality indicators (K232 and K268) related to oxidation processes with small datasets [2]. Such an approach also shows high interpretability, transforming deep learning from a black-box tool into a mechanism for understanding complex processes.

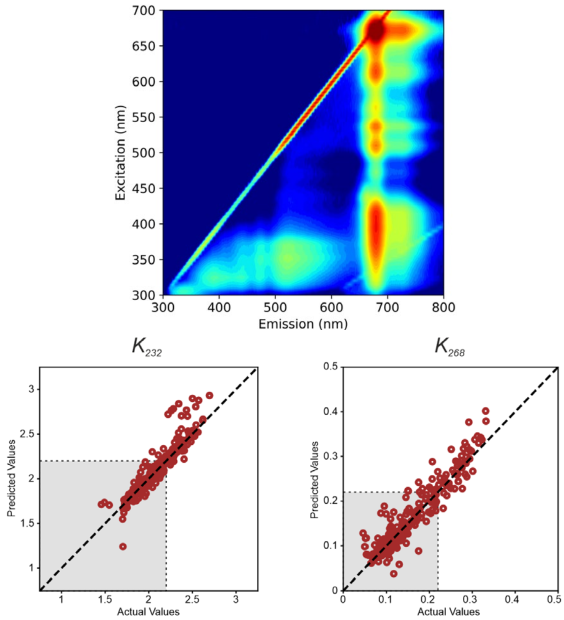

Fig. 3. Top: Excitation–emission matrix of EVOO. Bottom: Comparison of predicted and measured (actual) values of the quality indicators K232 and K268. The grey area in each plot marks the limit set by the Food and Agriculture Organisation of the United Nations and by the European Union. (Taken and adapted from [2])

Conclusions

The combination of optical sensors and DL offers substantial potential for improving agrifood quality assessment. Portable, low-cost devices powered by specific models enable accurate real-time monitoring of key parameters, as demonstrated in extra virgin olive oil. These innovations support sustainable and scalable solutions for food quality monitoring and open the door to a new generation of portable devices.

References

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