European Network for assuring food integrity using non-destructive spectral sensors (SensorFINT).

Prospective report on new emerging and innovative technologies for quality and process control in the agro-food industry I & 2.

1. INTRODUCTION

The agri-food industry is a very complex sector that faces growing challenges every generation. With globalisation, production processes in the food industry have become much more complicated. Current estimates have indicated that by2050, food production will have to double to supply the world's population demand, which will be approximately 9.8 billion by 2050 and 11.2 billion by 2100[1]. In addition, it is estimated that 930 million tonnes of food, or approximately 33% of all food produced in the world, is lost or wasted at some point in the agri-food supply chain, leaving 800 million people suffering from hunger [2],[3]. It is widely expected that new technologies have the potential to revolutionise agriculture completely [4], ensuring higher food production using fewer resources[5], reducing food loss and waste, and having overall better environmental implications [6].

Moreover, to the global challenges, consumers are increasingly demanding more information on the quality and safety of the food they buy. There is an emerging need for the food industry to provide information on its products in order to meetquality standards and to protect consumers from food fraud [7–11].The digitalisation of the agri-food sector enables these challenges to be addressed through precision mechanisation, automation and better decision making [12], aswell as greater control of traceability through the collection and exchange of real-time data information [13]. To improve the production and product quality, the solutions to be developed need to be innovative and sustainable. Although research on digitalised systems applied to the agri-food sector is a trend with a lot of promising innovative research, the introduction of this technology into actualproduction systems is still a challenge [14].

Compared to other sectors, the agri-food industry faces inherent hurdles due to the nature of foods. Food is a complex product composed of heterogeneous matrices, which may contain numerous ingredients in a single product and whose behaviour may change throughout the production chain, which could result in theformation of substances that are nutritionally important or that can affect the safety of the food. In addition to the high chemical and physical variability due toexternal factors such as soil or water quality.

In order to design new analytical methods, the trend has been to investigate non-target methods that enable products to be analysed and generate a unique fingerprint so information about the quality, safety and authenticity of the food canbe obtained. Non-Destructive Spectral Sensors (NDSS) combined with data analytics provide cost effective, added value solutions to a range of food industryproblems as well as, at the same time, opportunities for better understanding theirproducts and ingredients.

NDSS such as NIR Spectroscopy, Fluorescence, Raman or Hyperspectral imaging are currently one of the most attractive techniques for the agri-food sector, due to their rapid, non-destructive and environmentally safe assessment of multiple parameters in a variety of food products. These techniques have already been used as analytical methods during routine analysis of food ingredients and products [15], [16].

The high variability between products makes it necessary to select the most appropriate technique, the most efficient sampling method and a representative reference database for each type of product for the development of robust and efficient methodologies.

This report covers some of the new technological trends for quality and safety control in the agri-food sector, dividing the content into the three most important aspects of implementing this technology: advances in instrumentation, sensor fusion and spectral data processing and transmission.

2. INSTRUMENTATION DEVELOPMENT

Because of their simplicity, speed, selectivity, and ease of sampling, portable NDSS are becoming increasingly popular and are ideal for taking spectra in non- laboratory environments [17]. There are numerous studies evaluating this type ofequipment with all kinds of samples in the agri-food sector [18–21]. However, most studies are carried out in laboratories, although the trend is to implement this equipment in fields and factories [22], [23], because they are inexpensive anddo not require expert operators to carry out the analysis .One of the main objectives in instrumentation development is to achieve robust systems that canbe used in harsh environments such as the field or the production line and flexiblefor both in-situ and on-line measurement. The two strategies usually adopted to attempt these objectives are the miniaturisation of spectrometers [24], [25] and the design of both single and multiplex fibre optics [26], [27].

Since the last decade, miniaturised spectrometers have been the main trend in innovative instrumentation research because they are compact, lightweight and inexpensive, making their implementation in real environments outside the laboratory very feasible [28]. The first miniaturised devices had external radiationsources and were mains powered, so their applications in the field were not possible. Advances allowed the design of medium-sized sensors that are hand- held NIR systems, that include all the necessary elements to be used autonomously, such as the battery or electronic controls. Developments in microelectronics and MEMS (microelectro-mechanical systems) have made it possible to move from medium-sized equipment (around 1.5 kg) to micro spectrometers (over 100 g) [28] (see Figure 1.). One of the main challenges facing the development of micro spectrometers is that the large majority of themhave no internal self-test protocols to ensure long-term stability and robustness, and there are currently not enough studies on this subject. The main attraction for companies of this equipment is its low cost, so that several of these sensors can be implemented along the production chain, however, regarding NIRSimplementation, it is necessary that the models can be transferred between units.Otherwise, the low cost of the equipment will be compromised by the high cost of various calibrations, although there are studies that show that this transfer is possible [29–31].

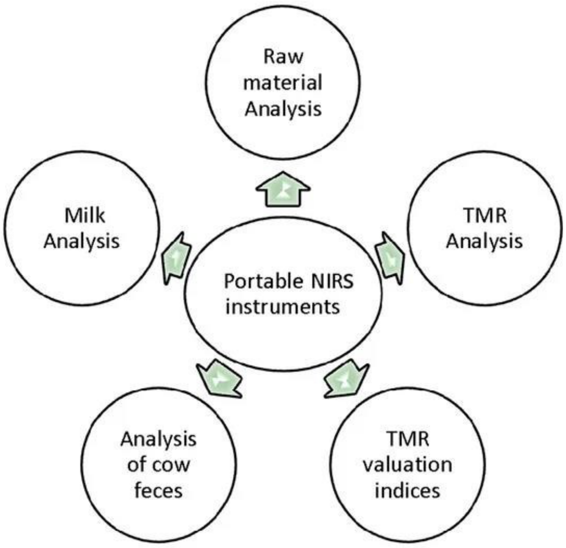
Figure 1. Comparison between medium-sized equipment (Phazir^{TM}) and micro-equipment (MicroNIR, VIAVI Solutions Inc.).

Despite all the advantages of miniaturised equipment, it is true that in some casessampling is very complex, and one of the best instrumental strategies is the use of optical fibres, either single or multiplex fibres for parallel analysis [26], [27], [32]. When comparing miniaturised equipment with fibre-optic probes and laboratory equipments, it has been found that, although the performance is lower,the fact that it can be carried out on´site and in-line itself is of greater interest to industry than the possible loss of accuracy [28].

While the development of compact equipment is one of the main lines ofresearch, the integration of micro-spectrometers into smartphones is another of the newest and most common trends in recent years [33], [34]. Currently, the move from micro-equipment to ultra-miniaturised devices is underway, which means the possible integration of this equipment in new fields and with innovativeapplications.

To conclude the instrumentation block and in connection with the next one, sensor fusion, it is worth mentioning one of the most revolutionary trends in precision farming, robots equipped with NDSS can traverse fields, collecting spectral data and providing valuable insights for proactive crop management (seeFigure 2**.**) [35], [36].It will allow tasks that would be challenging or time-consumingfor humans to perform efficiently and accurately. As technology advances, we can expect further innovations in this field with new applications and improved robotic and spectroscopic capabilities.

Figure 2. Schematic representation of portable NIRS instruments use in dairy farms. From



reference [37].

3. NON-DESTRUCTIVE SPECTRAL SENSORS FUSION

Despite the great potential of NDSS, one technique alone often does not provideenough information. Consequently, there is a growing trend for sensor fusion strategies. It has the potential to enhance productivity, reduce waste and contribute to the creation of sustainable and advanced technology in the agri-foodsector. The fusion of non-destructive spectral sensors allows for the integration of data across the entire agrifood supply chain. From the field to processing anddistribution, these sensors generate a wealth of data that, when properly analysed, provides actionable insights.

Hyperspectral imaging systems (HIS) combines the advantages of spectroscopy and machine vision in addressing food quality, authenticity, and safety problems.By capturing a broad range of spectral bands, hyperspectral sensors can providedetailed information about the composition of fruits, vegetables, and grains. HIS integrate spatial and spectral details together [38], can not only detect biochemical and physical properties of samples, but also their corresponding spatial distribution. This technology enables the identification of subtledifferences in products quality, facilitating sorting and grading processes with unparalleled precision.

HIS is a technique that is closely linked to horticultural research, and nowadays there are many publications on the subject [39]–[41], as well as animal feed [42], [43] and meat products [44], [45]. Recently, new applications such as thedetection of microplastics [46], [47], pollutants [48] or the detection of early infections [49], [50] are a trend using HIS.

In addition, HIS improves the representativeness of the sample, as large sampleareas are rapidly scanned to obtain average spectra representative of larger portions of the sample compared to using a single NDSS, an advantage that alsobrings new challenges, because large amounts of data need to be processed [28]to obtain satisfactory results. This topic will be discussed in the next section.

While the fusion of non-destructive spectral sensors holds great promise, challenges include the need for standardization, calibration, and the developmentof user-friendly interfaces for industry adoption [43]. Ongoing research aims to address these challenges and unlock the full potential of these technologies in the agrifood sector.

4. DATA TREATMENT AND STANDARDIZATION FOR THETRANSFER OF NIR SPECTRA

NDSS generate vast amounts of spectra data, the treatment of this data is a critical step that involves preprocessing, calibration, and analysis. Advanced algorithms, including chemometrics and machine learning, are applied to extractmeaningful information about factors such as nutrient content, moisture levels, and disease presence. This treatment process enhances the accuracy and reliability of the insights derived from spectra data.

As already outlined above, the complex food matrix makes the development of robust models more complicated compared to other sectors, such as the pharmaceutical sector. For the integration of this technology in the agri-food sector, it must be necessary to develop accurate models with high reproducibilityrates between devices, which currently requires an investment in good chemometric developments and their maintenance over time.

One of the main trends arising from the wide range of modern NDSS applicationsis that a large amount of generated spectra data will not correspond to any reference value [51], i.e. there is a growing trend towards the development of semi-supervised or even unsupervised models built from unlabeled samples [51–53].

As mentioned throughout the present report, the trend towards sensor fusion is increasing, which means that classical chemometric methods such as principal component analysis (PCA) and partial least squares regression (PLS) are sometimes not suitable for dealing with satisfactory models [55]. In order to carryout these analyses, multiblock methods have been developed in recent years. Using multiblock analysis, it is possible to obtain complementary information fromthe various techniques employed [56], this type of analysis provides insight into common and distinct information from data obtained from different sensors [57], [58].

5. CONCLUSION

Finally, one of the goals for the future is the promotion and application of cloud computing platforms, as despite the development of many new chemometric methods, instrument software is often not updated [51]. From cloud platforms, spectra data from different sources, such as different points in the production line,can be managed and stored, which will enable automatic optimisation processingand the application of spectra big data [59].

the agri-food industry, confronted with increasing challenges, is poised for transformation through technological innovations. The integration of new technologies, particularly digitalization, holds the potential to revolutionize the agri-food sector, ensuring higher production with fewer resources and minimizing environmental impact. Consumer demands for information on food quality and safety are rising, requiring transparency in the food industry to meet quality standards. Digitalization enables precision mechanization, automation, and real-time data exchange, addressing these challenges and enhancing decision-making.

The report emphasizes the importance of selecting appropriate techniques, efficient sampling methods, and representative reference databases due to the high variability between food products. Instrumentation development is focused on portable NDSS, with an increasing trend toward miniaturization. Sensorfusion, combining different NDSS, is identified as a crucial trend to enhance productivity, reduce waste, and create a sustainable agri-food sector. Hyperspectral imaging systems, integrating spatial and spectral details, prove valuable for addressing food quality, authenticity, and safety issues. Challengesin standardization, calibration, and user-friendly interfaces are acknowledged, requiring ongoing research for industry-wide adoption. Data treatment and transmission involve the critical step of preprocessing, calibration, and analysis of the vast spectral data generated by NDSS. Advanced algorithms, including chemometrics and machine learning, are employed to extract meaningful information. The complexity of the food matrix poses challenges in developing robust models, emphasizing the need for accurate and reproducible models across devices.

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NOTE: The SENSORFINT MC finally decided to develop these two deliverables in the form of a Special Issue in a scientific journal, providing opportunities for the participant to submit research and review papers, and to show the collaborations established during the Action.

After evaluating different journals, the special issue was agreed with the journal Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy (a first quartile scientific journal). The SensorFINT Chair and Vice-Chair acts as Guest Editors of this Special Issue. The title of the special issue is: *Applications, trends and challenges of emerging and innovative non-destructive spectroscopic sensors for the assessment of food integrity issues along the entire food supply chain.*

https://www.sciencedirect.com/special-issue/312844/spectral-sensors-food-integrity

It has been agreed that this SENSORFINT Special Issue will have around 14 articles, with an estimated of 10-12 research papers and 3-4 reviews. The deadline for submission of articles is December 2024 and the expected publication date March 2025, after the peer review phase.

The current situation is that we have 8 submissions under review and we are waiting for the rest of the proposals, for which we count on the commitment and communication of many of the participants.