**Low-cost and Novel Sensors for Fruit Maturity Assessment Along the Whole Quality Chain**

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This Ph.D. project aims to develop non-destructive method for estimating apple maturation during pre-harvest and post-harvest using Electrical impedance spectroscopy (EIS) and optical techniques. It focuses on developing a portable impedance analyser, and a machine learning-based classification method for fruit ripening discrimination. Machine learning approaches will be used to develop models for discriminating apple ripening status. Data analysis of optical spectroscopy and bioimpedance using machine learning will be optimized, tested, and compared to provide efficient real-time estimation of apple ripeness at pre-harvest and post-harvest stage. This model objective is to empower local companies to optimize apple production, storage, and processing for improved efficiency and sustainability.

**Sensori innovativi ea basso costo per la valutazione della maturità della frutta lungo l'intera catena della qualità**

Questo dottorato di ricerca Il progetto mira a sviluppare un metodo non distruttivo per stimare la maturazione delle mele durante la pre-raccolta e la post-raccolta utilizzando la spettroscopia di impedenza elettrica (EIS) e tecniche ottiche. Si concentra sullo sviluppo di un analizzatore di impedenza portatile e di un metodo di classificazione basato sull'apprendimento automatico per la discriminazione della maturazione dei frutti. Verranno utilizzati approcci di apprendimento automatico per sviluppare modelli per discriminare lo stato di maturazione delle mele. L'analisi dei dati della spettroscopia ottica e della bioimpedenza utilizzando l'apprendimento automatico sarà ottimizzata, testata e confrontata per fornire un'efficiente stima in tempo reale della maturazione delle mele nella fase pre-raccolta e post-raccolta. L'obiettivo di questo modello è consentire alle aziende locali di ottimizzare la produzione, lo stoccaggio e la lavorazione delle mele per una maggiore efficienza e sostenibilità.

**1. State-of-the-Art**

Apples are among the most popular consumed fruits in the world. The European Union is one of the biggest apple producers, after China. With a share of 19.2% Italy is the second European producer after Poland (25%) (https://ec.europa.eu/eurostat (accessed on 18 July 2021). The total apple production of EU was 12.2 million tons in 2020 (https://www.statista.com/statistics/577753/apples-production-volumeeuropean-union/, accessed 18 July 2021)(DeMeyer, 2014). To maintain the check on quality and ripeness assessment of apple throughout all stages of production is crucial for meeting consumer demands, reducing food waste and improve the profit margin of producers. Food and Agriculture Organization of the United Nations (FAO) refers to fruit waste as “the decrease in the quantity or quality of fruit resulting from decisions and actions by retailers, food service providers and consumers” (Angelo Zanella and Sadar Nadja, 2021). At each stage of the fruit supply chain, from cultivation to final consumption, fruit quality assessment is integral to reducing financial losses. The post-harvest sorting of fruit is particularly essential, with both internal and external quality attributes and defects considered in identifying damages caused by mishandling - mostly related to mechanical (pressure, impact) and temperature (freezing, thermal shocks) issues (Jha *et al.*, 2019).

A range of techniques exist to assess fruit quality before harvest and post-harvest, with correct determination playing a key role in the entire supply chain management. For the quality of apples following parameters are included; firmness, texture, core color, internal flash color, soluble solids concentration (SSC), starch, soluble sugars concentration, chlorophyll content for maturity of fruit, and the internal disorder (Li and Thomas, 2014). However, dealing with overripe fruits during postharvest is a challenging task that results in negative impacts on their storage and marketing (Atkinson *et al.*, 2014). These all parameters are analysed by conventional destructive techniques and non-destructive techniques. At present, destructive methods are widely investigated, their qualitative and quantitative measurements are very precise and accurate, and high sensitivity, for instance, dynamometer for firmness, refractometer for sugar concentration and starch index for ripening. However, these techniques also have many limitations; expensive, long wet lab based experimental set up, slow, time-consuming, and require sample preparation, thus they cannot be used for large-scale measurement, for instance in field and in food sheds, and storage houses. This method also creates damage in the sample which is not ideal for industrial purposes (Srivastava and Sadistap, 2018).

To overcome the wastage of food and for environment safety, non-destructive technologies are recently developed and attract market attention because it allows repeated quality measures on the same fruits without damaging it. With increasing demands for real-time detection of fruit quality at the industrial level, it is necessary to develop non-destructive and non-contact detection systems (Nicolaï *et al.*, 2007).The most common used non-destructive analysis are optical techniques, based on the interaction of the light with the sample under test, include colorimetry (Reid, 2002), visible imaging (Vanoli and Buccheri, 2012), visible and near-infrared (VIS-NIR) spectroscopy (Cortés *et al.*, 2019), hyperspectral and multispectral imaging (Qin *et al.*, 2013). However, the most common use NIR technique for fruit quality has some limitation too; 1) Low sensitivity, 2) wavelength overlap, 3) Not able to provide the full image of internal physiology of fruit, 4) Penetration of light is very few milli meter, 5) Not able to identify internal disorder and internal browning of fruit directly, 5) NIR spectra of fruits is dominated by water absorption bands.

On the other hand, the interaction of an electric field with the fruit provides a new approach for fruit quality measurement. In this context, Electrical Impedance Spectroscopy (EIS) represents a low-cost and competitive approach compared to conventional optical methods (Ibba *et al.*, 2018). Electrical impedance spectroscopy (EIS) has shown promise as a suitable method for detecting changes in fruit physio-chemical properties(Rivola *et al.*, 2021). However, its potential in the context of fruit quality control is limited by technical constraints such as the need for bulky and expensive instrumentation, non-optimized electrode systems, and a lack of data analysis methods. Thus this Ph.D. project aims to address these issues by combining bio-impedance measurement with optical techniques like Near-Infrared spectroscopy to develop a more precise comparative model. While NIR is commonly used for fruit quality analysis, it lacks real-time assessment of internal physiology and browning (Mohsen *et al.*, 2021). This study aims to resolve this limitation by incorporating non-destructive techniques to improve precision and accuracy in evaluating fruit quality.

# **2. PhD Thesis Objectives and Milestones**

Within the overall objective mentioned above this PhD thesis project can be subdivided into the following activities according to the Gantt diagram given in Table 2:

A1) **Literature Review** Current progress in utilizing EIS and optical spectroscopy for managing fruit quality and maturity parameters.

A2) **EIS and other non-destructive spectroscopic analysis** To enhance the connection between electrical and biological data, there will be efforts to correlate the bioimpedance data with the physiological changes in fruits and create new equivalent circuit models that provide a more accurate representation of the interaction between fruit quality and bioimpedance.

A3) **Comparative statistical data analysis for efficient bioimpedence model** To advance the data analysis of bioimpedance data and NIR data then its correlation with the maturity of fruit. To develop a comprehensive data analysis pipeline, including the data acquisition, reduction, transformation, and correlation, to achieve (i) a flexible platform to follow during future studies in the field and (ii) the first prediction and classification models of apple aging evolution starting from bioimpedance data.

A4) **Application of the comparative model to pre-harvest and post- harvest fruit samples** To design and validate new, affordable, and adaptable portable impedance analyzers that are specially intended for the purpose of fruit aging monitoring throughout the entire supply chain to bridge the gap between this comparative bioimpedence measuring model and its practical application in the field.

A5) **Writing and Editing** of the PhD thesis, scientific papers and oral and/or poster communications.

***Table 1***Gantt diagram for this PhD thesis project.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Activity Months | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** | **21** | **22** | **23** | **24** |
| A1) | ***Literature Review*** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| A2) | ***EIS and other non-destructive spectroscopic analysis*** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 1) EIS at pre and post-harvest |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 2) Optical analysis for different quality parameters |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| A3) | ***Comparative statistical data analysis for efficient bioimpedence model*** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 1) Correlation with other analytical analysis tool |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 2) Best fit model Prediction |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| A4) | ***Application of the comparative model to pre-harvest and post- harvest fruit samples*** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 1) Validation of comparative model |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 2) Application on samples |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| A5) | ***Thesis and Paper Preparation*** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

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