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Bachelor's project in Mechanical Engineering
Supervisor: Anna Olsen and Eirin Marie Skjøndal Bar
June 2020

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NTNU
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PROBLEM DESCRIPTION

According to the Food and Agriculture Organization of the United Nations (FAO), one third of the globally produced food for human consumption is lost or wasted every year, leading to an approximate amount of 1.3 billion tons per year (FAO, 2011).

Most people would consider this figure to be far too high, representing a waste of labour, water, energy, land and other precious resources and inputs that were used during the food's production. Moreover, it also represents excessive greenhouse gas emissions created during production and transportation of the wasted food, which are, in effect, emissions in vain (FAO, 2011).

Although food is lost or wasted at every stage of the supply chain, in medium- to-high-income countries, food is most significantly wasted at the consumption stage (FAO, 2011). This leads us to the point that it has been proven that in supermarkets many vegetables and fruits are being thrown away because they need to include an expiry date, making them unsaleable beyond this point. Another factor contributing to fresh food waste are the rigorous "appearance quality standards" in place at many first world supermarkets, meaning that many products are discarded simply because they do not reach certain cosmetic standards, even though nutritionally they may still be perfectly suitable for human consumption (FAO, 2011).

Since these statistics are alarming, there have been several investigative programs and studies with the aim of determining fruit quality.

When discussing fruit quality there is an extremely wide range of different parameters that could be considered to determine this concept. However, from a consumer point of view, the state of ripeness is one of the most important factors, making it a crucial parameter for the consumer when buying the product.

This is the main reason why, in recent years, a considerable number of research projects have been carried out with the aim of finding a way to evaluate fruit ripeness. However, the correlation and relationship between these different parameters hasn't yet been fully analyzed.

Therefore, the purpose of this thesis is to study and evaluate the different techniques that could determine fruit quality in a supermarket environment and evaluate and establish a relationship between the measurable parameters. Consequently, with this project I am aiming to contribute to food quality research as well as to go a step closer to reducing food waste.

ABSTRACT

In this thesis, some of the different parameters that can determine fruit ripening have been measured and analyzed through non-destructive techniques by following the ripening process of three different kinds of fruits: mangoes, bananas and avocados. The parameters analyzed were the electrical impedance, electrical phase, weight and colour of the fruit.

Therefore, the experimental measurements took all place in a room maintained at an average temperature of 20 degrees. The fruit was kept in this room at all times throughout the experimentation period, keeping it stable and avoiding external influences affecting the ripening parameters. The measurements were carried out every day at 13 pm for a period of 12 days**.** The electrical impedance was measured with an AD5933 board between the frequencies of 1kΩ and 100 kΩ. The weight was measured with a kitchen scale and the colour was evaluated through both the pictures and the Fiji software.

Finally, the results showed that, in reference to the weight evolution, all of the three fruits follow a linear decreasing evolution, following similar mathematical slopes.

In reference to the electrical impedance, the results showed that the impedance of mangoes increases when these fruits ripen, while the banana's decreases. The evolution of the avocados impedance, however, follows an irregular behaviour. Moreover, the measurements showed that the angle stays constant during the ripening process and that there is not a huge or significant variation of colour composition throughout the ripening days.

Finally, the relationship between the electrical impedance and the weight was analyzed, as well as the sensitivity of the electrodes.

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1 INTRODUCTION

Food Waste is one of the biggest problems facing humanity in the 21st century, leading to an approximate amount of 1.3 billion tons of food wasted every year (FAO, 2011). Even though food is wasted throughout the supply chain, food is most significantly wasted at the consumption stage (FAO, 2011). In supermarkets, many packaged fruits and vegetables are being thrown away simply because of the requirement of 'sell by' dates, and once this has passed they become impossible to sell, even though nutritionally they may still be perfectly suitable for human consumption (FAO, 2011).

When talking about fruit quality, there is an extremely wide range of different parameters that could be considered to determine this concept. However, from a consumer's point of view, the state of ripeness is one of the most important ones, making it a crucial parameter for the consumer when buying the product.

This is the main reason why further research on food ripeness needs to be done, both to contribute to food quality research as well as to get a step closer to reducing food waste.

Consequently, with this project I am aiming to both contribute to food quality research as well as to get a step closer to reducing food waste.

1.1 BACKGROUND

Several studies have been carried out concerning fruit ripening assessment through electrical impedance spectrometry. There are some examples, such as:

- Monzurul Islam et al, 2018. **Assessment of Ripening Degree of Avocado by Electrical Impedance Spectroscopy and Support Vector Machine.**
  Review: *This work presents a study of EIS and machine learning technique that could allow monitoring the ripening degree of the avocado (Monzurul Islam et al, 2018).*

- N.V.Mane et al., 2017.**Banana Ripeness Assessment by Impedance Spectroscopy.**
  Review*: The aim of this work was to correlate the impedance variation during the ripening process of bananas (N.V.Mane et al., 2017).*

- Pietro Ibba et al., 2020.**Bio-impedance and circuit parameters: An analysis for tracking fruit ripening.**
  Review*: This study deals with the effect of ripening on apples and bananas using a microcontroller-based EIS system (Pietro Ibba et al., 2020).*

- Mahfoozur Rehman et al., 2011. **Assessment of quality of fruits using impedance spectroscopy**.
  Review: *In this study, they worked with the development of a nondestructive impedance spectroscopic technique that could be able to assess the conditions of the fruits (Mahfoozur Rehman et al., 2011).*

- Atanu Chowdhury. P. Singh, Tushar Kanti Bera, D. Ghoshal1, Badal Chakraborty. **Electrical impedance spectroscopic study of mandarin orange during ripening.**
  Review*: The goal of the work was to study the electrical impedance variations and variations in weight of the orange fruit with different ripening states (Atanu Chowdhury. P. Singh, et al, 2017).*

However, the relationship between non-destructive parameters that could be measured in a supermarket environment, such as weight and colour, has not yet been analyzed in the same experiment. Therefore, it is believed that with this project further studies and results could be obtained.

1.2 GOALS AND SCOPE

The main goal of this project is to study and evaluate the different measurable parameters and techniques that could determine fruit quality in a supermarket environment and evaluate and establish the relationship between the measurable parameters.

Therefore, the purpose of this thesis is to study and evaluate the different techniques that could determine fruit quality in a supermarket environment and evaluate and establish a relationship between the measurable parameters

To do so, the ripening process will firstly be studied, as well as all the phenomena that fruit undergoes during the ripening process, physically, chemically and biologically.

Following this, all the different measurable parameters and techniques that could determine the fruit quality in a supermarket environment will be studied, and the ones suitable for the purpose of the project will be chosen.

Finally, all the chosen techniques will be used to conduct an experiment to evaluate the ripening process of different fruits. Furthermore, the results obtained will undergo statistical analysis so as to both, understand the behaviour of the results and establish a relationship between some of the measured parameters.

Below is an outline of the goals that have been set and that will be developed throughout the project:

- To study the ripening process and understand the measurable parameters that determine fruit quality
- To identify the different parameters that could be measured during the ripening process from the literature
- To build the experimental set up to measure the chosen parameters.
- To analyse the results obtained and establish a relationship between them.

On the other hand, the scope of this project is to analyze three different fruits: mangoes, bananas and avocados.

The main aspects that have been considered for this choice are:

- All these fruits have different structures and it will be interesting to analyse the results obtained and to be able to compare them.
- They change their aspect and colour during the ripening process, making it possible to relate each ripening status with the visual appearance.
- Due to the different geometry of these fruits, the variations in results obtained thanks to various different dispositions of the electrodes could be analysed.

Consequently, with this project I am aiming to contribute to food quality research as well as to get a step closer to reduce food waste.

1.3 FURTHER INNOVATION

As will be shown in the next chapters, this project used an AD5933 board to measure the electrical impedance spectrometry. This board, even though it exhibits a lower level of sophistication in contrast with other laboratory tools, it also presents some advantages such as easy portability (Pietro Ibba et al., 2020).

Consequently, it is believed that utilizing this kind of method would be one of the best ways of creating a device that could easily be workable in a supermarket environment in order to obtain information about the fruit’s ripening state.

Therefore, the data and results obtained in this project regarding fruit ripeness with the electrical impedance spectrometry are believed to be a very useful tool for further studies to improve this conceptual device and build a physical prototype.

2 THEORY

Before even starting the project it was first necessary to understand the theoretical background of fruit ripening and the phenomena that occur during the process.

Therefore, this first section follows the aim to discover the phenomena of fruit ripening, as well as the parameters that determine whether a fruit is ripe or not. Moreover, the different possible techniques to experimentally determine the quality of the fruit will also be studied.

Following this broad study, these techniques will be evaluated and the best technique for the aim of the project will be chosen.

2.1 FRUIT RIPENING

Fruit development involves different phases, which include the development of the ovary, cell division and increase of the fruit in size by cell expansion. Once these phases have been completed successfully, the ripening process begins (Avatar k. et al., 2012).

This ripening process converts a hard, unappealing fruit into a colourful nutritious product that attracts birds, animals and humans to aid in seed dispersal (Shan Li et al., 2019).

Therefore, the ripening process includes changes where, in general, fruit becomes sweeter, softer and less green and to do so, this process is regulated by both genetic and epigenetic factors (Avatar k. et al., 2012).

Consequently, during the ripening phenomenon, the fruit undergoes different changes including texture and firmness (by consequence of changes in the composition and softening of the cell walls of fruits), sugar accumulation, reduction in organic acids, alterations in pigments that lead to development of a less green colour and also the production of volatiles gases such as ethylene (Avatar k. et al., 2012).

2.1.1 Climacteric and non-climacteric fruits

When discussing fruit ripening, the classification between climacteric and non-climacteric fruits cannot be ignored.
This classification is based on respiration patterns:

- **Climacteric fruits:** They are defined as fruits that continue to ripen after harvest (Dr. K.Sujatha et al., 2016). These kinds of fruits emit ethylene gas along with a rise in respiration during the ripening process (Dr. K.Sujatha et al., 2016).

- **Non-climacteric fruits:** These kinds of fruits do not further ripen once harvested and they produce insignificant amount of ethylene gas (Dr. K.Sujatha et al., 2016). Moreover, there isn't an increased rate of respiration (Dr. K.Sujatha et al., 2016).

Further on, this ethylene gas production will be evaluated and studied.

Herein, a table containing a classification of climacteric and non-climacteric fruits is attached:

Table 1. *Climacteric and non-climacteric fruits examples (Kaushlendra Tripathi et al., 2016, p. 1)*

Climacteric		Non-climacteric
Apple	Tomato	Grape
Avocado	Watermelon	Limon
Banana	Passion fruit	Orange
Mango	Kiwifruit	Strawberry
Papaya	Apricot	Pomegranate
Pear	Fig	Raspberry
Melon	Cantaloupe	Cucumber

It is important to state that since the aim of this project is to evaluate the ripening of fruit, it will be necessary to study climacteric fruits rather than non-climacteric fruits.

2.2 FRUIT DAMAGE

Fresh fruits are very susceptible to mechanical and thermal damage during harvesting, packaging and transport (Zhiguo Li et al., 2014). Therefore, this can result in a substantial reduction in quality (Zhiguo Li et al., 2014). In this section, the different types of damage that fruit can go through will be evaluated, as well as the impact that this phenomenon could produce in the project's results.

For the purpose of this project, the main damaging parameters that will be evaluated will be those caused by **mechanical** and **thermal** aspects, as they will be the ones having most impact on the project.

2.2.1 Mechanical damage

Mechanical damage to fruits mainly occurs during field harvesting operations but it can also happen on packing lines, during transport and even at the end of the supply chain, for instance, in supermarkets during selection by consumers (Zhiguo Li et al., 2014).
There are different types and sources of mechanical damage:

- **Impact damage**
  This kind of damage occurs when an item hits a surface with sufficient force to rupture or even separate cells with an external sign of a bruise or crack (Zhiguo Li et al., 2014). It may occur when fruits fall to the ground during harvesting or packaging, but can also be caused by vibrations during the transportation process to consumers (Zhiguo Li et al., 2014).

- **Compression damage**
  Compression damage occurs mainly during or after packing as a result of putting too much product into a container, which is too small (Zhiguo Li et al., 2014).

- **Abrasion**
  This occurs during movement of one body against another, which leads to the removal of surface layers (Zhiguo Li et al., 2014). This kind of damage can occur during different stages of the fruit ripening process, such as while harvesting, when conveying at excessive speed or during packaging (Zhiguo Li et al., 2014).

- **Puncture**
  This may occur during harvesting and manipulation of loose fruits when the stems of the harvested fruits perforate the skin of neighbouring fruits (Zhiguo Li et al., 2014).

All of these can result in structural tissue and cell damage to fruits caused by several actions combined, and with this structural failure, susceptibility to decay and growth of microorganisms may increase (Zhiguo Li et al., 2014).

2.2.2 Thermal damage

The amount of time food is stored, as well as the conditions in which it is stored before eating, often affects its quality (Jody Braverman, 2020). Therefore, the temperature in storage also affects the food quality.

Consequently, temperature extremes of hot and cold accelerate spoilage and cause fruit damage (Rebecca Bragg, 2020). These extremes can also be reached during different stages of the fruit ripening process, such as during harvesting, transportation and at the final place of storage.

It should be noted that some of the parameters leading to fruit rotting are beyond our control. However, some mechanical damage is immediately apparent from the fruit's appearance. Therefore, in order to more closely control factors that could affect the experiment's results, fruit with signs of mechanical damage e.g. abrasions, punctures and bruises, will be avoided in this study.

Furthermore, we have no way of determining whether the fruit has been stored in optimal temperature conditions before reaching us, but for the purposes of this experiment it will be kept in a mild environment during the experimental period, avoiding extremes of heat of chill that could affect the experiment's results.

2.3 PARAMETERS THAT DETERMINE FRUIT RIPENING

2.3.1 Ethylene production

Ethylene is a gas produced by a plant hormone, which, as previously noted, plays a critical role during the ripening process of climacteric fruits (Avatar k. et al., 2012). Not only is it involved in fruit ripening, but also in other aspects of plant growth and development (Avatar k. et al., 2012).

Therefore, this phytohormone regulates fruit ripening by coordinating the expression of genes that participate in multiple biological processes (Yudong Liu et al., 2020).
Consequently, during fruit ripening, the ethylene biosynthesis process happens, producing and ejecting this gas into the atmosphere. In climacteric fruits, during the ripening process the production of ethylene gas can increase up to 100-fold during the fruit's transition from low concentration to a major autocatalytic ethylene synthesis (Shan Li et al., 2019).

2.3.2 Weight loss

Several scientific studies have also proved that fruits lose weight when ripening. This percentage of loss can be calculated as:

$$Weight\ loss\ \% = \frac{Fruit\ weight - Underripe\ fruit\ weight}{Underripe\ fruit\ weight} * 100$$

2.3.3 pH change

Results obtained with several earlier reports show that pH of fruit increases while ripening (for instance, Gordon E Anthon et al., 2011). This represents a decline of titratable acidity (TA) and therefore, also of acid levels, and a decrease of organic acids concentration, such as citric acid (Gordon E Anthon et al., 2011). A portion of this change is due to the metabolic conversion of acids into sugars (Gordon E Anthon et al., 2011).

This leads us to the conclusion that acid concentrations in the fruit are declining with maturity.

2.3.4 Sugar accumulation

During fruit ripening, the sugar accumulation and concentration also increases. As has been mentioned before, a portion of this change is due to the metabolic conversion into sugars that increase the sugar concentration (Gordon E Anthon et al., 2011).

2.3.5 Firmness of the peel and texture

During the ripening phenomenon, the fruit undergoes various different changes, including texture and firmness, by consequence of changes in the composition and softening of the cell walls of fruits (Avtar K. Handa, et al., 2012). A considerable number of studies have proved that flesh firmness of fruit shows a strong decrease when ripening.

Fruit texture during ripening, especially softening, is an essential attribute that is also associated with increased susceptibility to microbial infection and therefore reduced postharvest life (Avtar K. Handa, et al., 2012). This phenomenon also results in a weakening of the structure and involves modifications to the components of the primary cell wall (Avtar K. Handa, et al., 2012).

In conclusion, fruit loses firmness and softens when ripening.

2.3.6 Alterations in pigments

As has already been stated, during the ripening phenomenon the fruit undergoes different changes, including alterations in pigments that lead to the development of a less green colour (Avtar K. Handa, et al., 2012).

Evaluating these changes during fruit ripening could give important information about the maturity status.

2.4 DIFFERENT WAYS TO DETERMINE FRUIT RIPENING

One third of globally produced food is lost or wasted every year (FAO, 2011). These statistics are obviously alarming and there have already been several research programs and studies aimed at determining fruit quality.

When discussing fruit quality, there is an extremely wide range of different parameters that could be considered to determine this concept. However, from a consumer point of view, the state of ripeness is one of the most important factors, making it a crucial parameter for the consumer when buying the product.

This is the main reason why, in recent years, a considerable number of research projects have been carried out with the aim of finding a way to evaluate fruit ripeness.

In the following sections the different existing techniques that are capable of determining fruit ripeness will be studied, and further on, they will be evaluated in terms of their correlation with the main purpose of the project.

2.4.1 Destructive techniques

These kinds of techniques have the inconvenience of requiring the destruction of the fruit.
In this subsection, the different destructive techniques that could be used to determine fruit ripening will be studied.

2.4.1.1 Starch index with iodine

During the ripening process, starch degrades into sugar, meaning that ripe fruit has a lower concentration of this component (Dr. K. Sujatha et al., 2016).

Thanks to this phenomenon, iodine can be used to determine the ripening status of the fruit, since this substance creates a black colour in reaction with starch (R.B smith et al, 1979).

***Figure 1**.Starch conversion for apples in different ripening status*
*(**Source:** < http://www.fao.org/3/y4893e04.htm >)*

2.4.1.2 pH increase and sugar accumulation

As has already been mentioned, pH and sugar accumulation are two parameters that also determine fruit ripening, since they both experience an increase in their value during ripening.

The ph value can also be measured with a pH meter, with the aim of determining the titratable acidity of the fruit in the different stages of ripeness (Gordon E Anthon et al., 2011). Additionally, sugar accumulation can be measured using a refractometer (Gordon E Anthon et al., 2011).

However, both of these processes require that the fruit first be liquefied in order to achieve accurate measurements (Gordon E Anthon et al., 2011).

2.4.1.3 Firmness of the peel and texture

As has previously been mentioned, fruit loses firmness and softens when ripening. Therefore, evaluating the firmness of the fruit is a very common method of determining its ripening status. Moreover, this is a very easy technique to use and from which results are available in just a few seconds.

The tool used to measure the fruit firmness is called a Penetrometer.

Although this physiochemical method appears to be very applicable for determining the ripeness of the fruit, as the firmness is directly related to its ripeness, this technique is also destructive, requiring the fruit to be cut into slices, and is therefore inappropriate for this project’s main goal (Shan L et al., 2019).

2.4.2 Non-destructive techniques

Contrary to destructive techniques, non-destructive methods can be used for evaluating fruit ripening without damaging the fruit in any way and therefore keeping it available for human consumption after the examination.
Consequently, non-destructive methods represent a good alternative for the aim of this project.
Herein, the various different non-destructive techniques will be widely studied and evaluated.

2.4.2.1 Index of absorbance difference (IAD)

This technique, used to evaluate ripening, is a non-destructive index based on spectroscopy. IAD represents the difference in absorbance between two different wavelengths, where the modifications of the index are related to the changes in the parameters that determine fruit ripening, such as chlorophyll content, ethylene emission, fruit quality traits, etc. (Gugliemo Costa, 2008).

Therefore, this index can determine the status of fruit ripening by calculating the absorption between two different wavelengths, as this spectrum changes along with the ripening process (Gugliemo Costa, 2008).

2.4.2.2 Ethylene gas analysis

Several different independent research projects have investigated how to utilize ethylene gas analysis for the purpose of studying the ripening status of fruit, as the biosynthesis of ethylene gas gives fundamental information about a fruit’s ripeness.

For instance, some studies have been conducted using an electronic nose as a method of tracking ripeness (Brezmes Llecha, Jesus, 2016). However, the results obtained showed that this method would be unworkable in a supermarket setting, as too much time would be required to obtain results and the influence of humidity and temperature could not be controlled in this environment (Brezmes Llecha, Jesus, 2016).

Furthermore, this method is really quite complex and even though there is evidence of a relationship between ethylene's biosynthesis and the ripeness level, we consider that, due to the complications of use and the inconclusive results obtained in past projects, for the main purpose of this project it is not the best method to employ.

2.4.2.3 Electrical impedance spectrometry (EIS)

Electrical impedance spectrometry is a fast, low cost method of investigating impedance spectrum variations in order to determine the ripening degree of fruit (Mahfoozur Rehman, et al., 2011).

This technique works because of the biological structure of fruits. As we know, fruit cells are composed of a cell wall, a cell membrane, and intracellular fluids (Monzurul Islam, et al., 2018). Moreover, the cells are suspended in extracellular fluids, composing the tissues that compose the fruits (Monzurul Islam, et al., 2018). These components are made of different materials and they therefore respond differently to electrical current:

- The extracellular and intracellular fluids act as electrolytes and they consequently conduct electricity when an electrical current is applied (Monzurul Islam, et al., 2018).
- The cell membrane is a protein-lipid-protein structure that exhibits capacitance to the current (Monzurul Islam, et al., 2018).

Therefore, the response that the fruit exhibits when applying an electrical signal is bioelectrical impedance. This is a complex quantity that varies with each fruit tissue composition and the frequency of the electrical signal applied (Monzurul Islam, et al., 2018).

Due to the composition of fruit cells, this electrical bioimpedance will have two electrical components: the real part of the impedance and the imaginary part, due to the capacitance that the cell wall exhibits.

Mathematically, impedance can be measured as:

$$Z\langle\theta = \frac{V\langle\theta}{I\langle\theta}$$

Consequently, this electrical impedance spectrometry is carried out by measuring surface potentials obtained when injecting a constant current, taking into account that it depends on the frequency applied, as it is a multifrequency analysis and a frequency-dependent impedance (Monzurul Islam, et al., 2018).

Therefore, the frequency response of the bioelectrical impedance of the fruit tissues depends on the different ripening states, making it possible to establish a good relationship between ripening and the electrical response (N.V.Mane et al., 2017).

2.4.2.4 Colorimetry

This technique associates ripeness with the alteration in pigments and changes in colour. The method therefore requires the use of equipment with optical sensors capable of identifying colour variations.

The Colorimeter is a tool used to determine fruit ripeness by evaluating the colouring of the fruit epidermis. It measures three different parameters: brightness, saturation and the tone.

A major disadvantage of using this method is that these devices are both expensive and complex to operate.

2.4.2.5 Weight

As previously stated, fruit loses weight when ripening. Therefore, measuring this weight change could give important information about the state of ripeness.

2.5 TECHNIQUES EVALUATION AND CHOICE

After analyzing the different parameters that determine fruit ripening and the methods that could be used to measure the fruit ripening state, in this section all these different methods will be analyzed with the aim of determining the best option to accomplish the goal of the project.

Therefore, it is important to keep in consideration the main goal of this project when deciding coherently the actions that will be developed.

As has already been stated, the main goal is to study and evaluate the different measurable parameters and techniques that could determine fruit quality in a supermarket environment, and establish a relationship between some of the measured parameters so that further research can benefit from this data.

Therefore, the concept developed to take the measurements needs to be capable of measuring the ripening state without destroying the fruit, so that it remains fit for consumption.

2.5.1 Destructive techniques analysis

Although the different destructive techniques appear to be quite effective in determining the fruit ripening state, they are not the best option, since they require the destruction of the sample. Consequently, the following techniques will be dismissed:

- Starch index with iodine
- pH increase and sugar accumulation measure
- Firmness of the peel and texture

2.5.2 Nondestructive techniques analysis

Since non-destructive methods can be used for evaluating fruit ripening without destroying the fruit and keeping it available for human consumption after the examination, they represent a good alternative for the aim of this project. Nevertheless, not all of them are likely to become part of the conceptual development.

To start with, it has been considered that, even though **the index of absorbance difference** and **ethylene gas analysis** are good methods, they will not be used during this project, as they are too complicated to develop. Therefore, they will be dismissed.

This leads us to the point that only electrical impedance spectrometry, colorimetry and weight capture will be considered and studied for this project.

Consequently, three different conceptual options will be evaluated:

1st option: Use the existing prototype and add colorimetry analysis.

2nd option: Test the existing prototype and set it up for other fruits.

3rd option: Create a new concept using electrical impedance spectrometry.

In the following sections, the different specifications and the resources needed to develop these conceptual developments will be evaluated.

2.5.2.1 Existing prototype with colorimetry

This first option allows us to use the existing prototype with the main purpose of improving the proposed concept.

The existing prototype consists of:

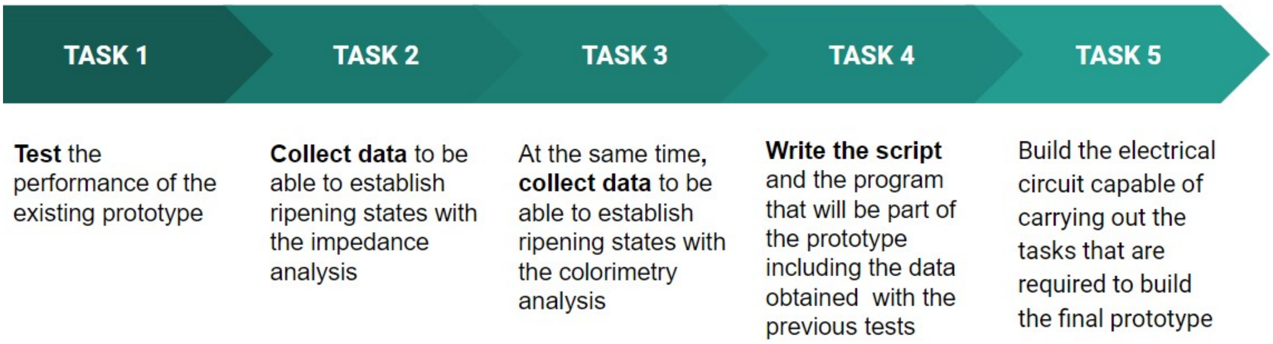
- One Arduino/ Raspberry pi
- One voltage divider
- Copper contacts and gel contacts
- LCD screen
- Capacitance circuit
- Resistance circuit

So as to improve this first concept, the main idea is to add another parameter able to determine the ripening state of the fruit. Accordingly, the answer that the user will obtain when using the prototype will be more accurate. Therefore, the colorimetry analysis method would be included.

Consequently, the purchase of a colorimeter (priced between 150-200€) would be necessary.

Therefore, the tasks to develop the technical part of this option would be:

Figure 2. *Tasks for the existing protoype with colorimetry*



2.5.2.2 Existing prototype set up for other fruits

This second proposal's main goal is to use the existing prototype with the main purpose of improving it by introducing measurements with other fruits. Therefore, its equipment would also be used to develop this second option:

- One Arduino/ raspberry pi
- One voltage divider
- Copper contacts and gel contacts
- LCD screen
- Capacitance circuit
- Resistance circuit

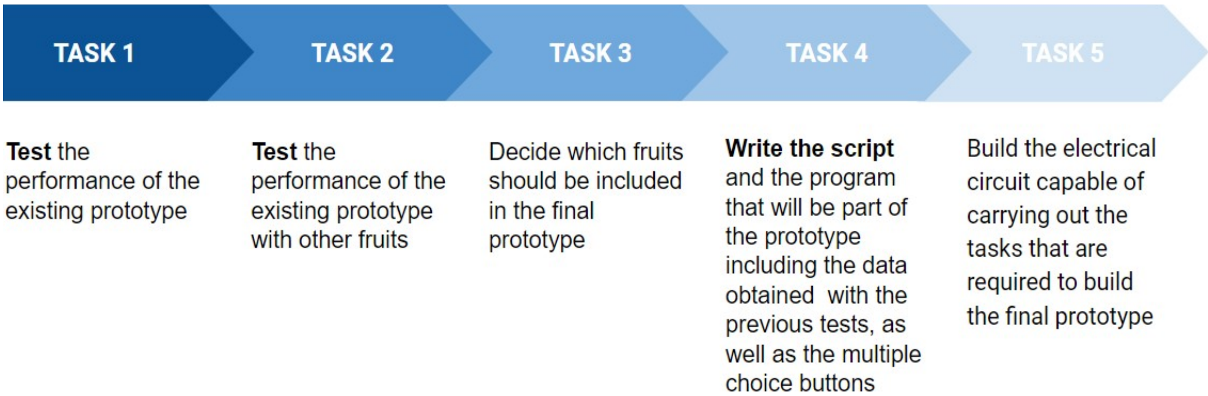
- Buttons pad

As we can see, this option will also include a button pad so that the user can choose which fruit is going to be tested.

Therefore, programming the button pad will also be required, as well as establishing the ripening status for all of the chosen fruits.

Different button pads can be purchased from 3€ to 15€.

Figure 3. *Tasks for the existing prototype with other fruits*



However, it is also important to remark here that before choosing whether to develop the first or the second prototype, it would firstly be necessary to check the performance of the existing prototype.

2.5.2.3 New concept with electrical impedance spectrometry

(This section includes a extensive information about the AD5933 impedance analyzer board. For more information about this board, see appendix C, that gives information about the data sheet of the board).

In the following subsection, the different materials and instrumentation required to build a new concept with electrical impedance spectrometry will be analysed.

As has already been stated, electrical impedance spectrometry is a technique that is carried out by measuring surface potentials obtained when injecting a constant current, taking into account that it depends on the frequency applied, as it is a multifrequency analysis and a frequency dependent impedance (Monzurul Islam, et al., 2018).

Therefore, the frequency response of the bioelectrical impedance of the fruit tissues depends on the different ripening states, making it possible to establish a good relationship between ripening and the electrical response.

Several research projects from the literature have tested the electrical impedance response of fruit with different instruments.

Some examples are:

- LCR meters
- Other laboratory impedance analysers such as Agilent 4294A or Solarton 1260A

All of these exhibit a wide range of test frequencies and high accuracy. However, these instruments are also expensive and require to be used in a laboratory environment, and are therefore not the best solution for the main purpose of the project.

In addition to this, several recent studies have shown that working with microcontroller-based EIS systems exhibit a major advantage in terms of cost and portability, even though they have some drawbacks in terms of accuracy due to their lower level of sophistication (Pietro Ibba et al., 2020).
Consequently, a good example of microcontroller-based EIS system is the AD5933. This instrument is an impedance converter system that combines an on-board frequency generator that allows an external complex impedance to be excited with a known frequency (Priya D.Shimpi, et al., 2015). Moreover, it also includes a device that allows the transmission of the results of the impedance measurements.

However, there are different types of AD5933 impedance analysers, and in the following sections, these options will be analysed:

Electrical impedance spectrometry with an AD5933 sensor
This kind of AD5933 board is a device that is composed of a sensor capable of analyzing the impedance (Pmod IA Reference Manual, 2016). However, it would need to be connected to an arduino or a raspberry pi to obtain and process the results analysed. Therefore, a lot of electronic and programming work would need to be developed before starting to analyse and calculate the impedance measurements.
An example of this sensor is the DigilentPmod IA:

Figure 4.*DigilentPmod IA AD5933 sensor (Source: <https://store.digilentinc.com/pmod-ia-impedance-analyzer/ >)*

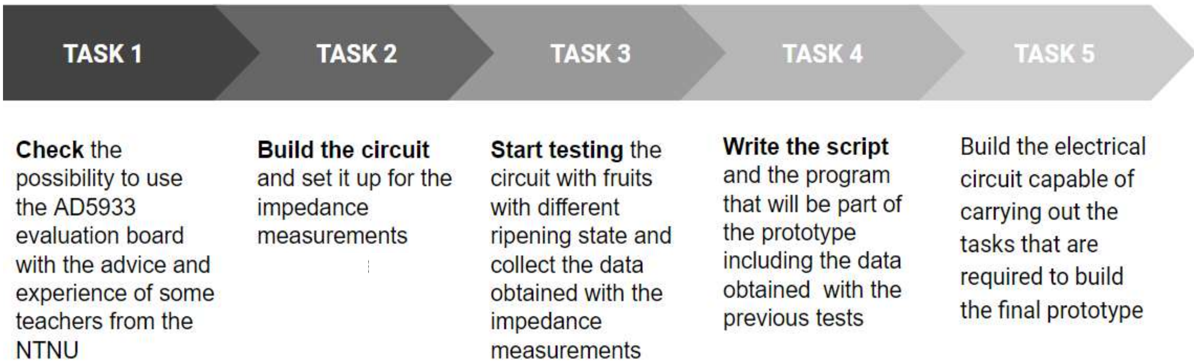
Therefore, it is believed that this instrument could be a good option to build a concept that could be used without a computer to process the data.

For this option, the following components would be required:

- One Arduino/ raspberry pi
- Two electrodes
- LCD screen
- Buttons pad
- Electric cables and jumpers
- Voltage divider

Herewith, a figure of the tasks that would be carried out with this conceptual development option is attached:

Figure 5. *Tasks for the prototype with an AD5933 sensor*



Electrical impedance spectrometry with an AD5933 microcontroller

Contrary to the Digilent Pmod IA, this device is an AD5933 board that has been fitted with a microcontroller. Therefore, this kind of AD5933 is “a high precision impedance converter system that combines an on-board frequency generator” (Analog devices, Data Sheet). This frequency generator allows an external complex impedance to be excited with a known frequency” (Analog devices, Data Sheet). Moreover, the user has the option to power the entire circuit from the USB port of a computer.

Therefore, this device can be connected straight away and controlled from a computer, as well as process and obtain the measurements. Consequently, an arduino wouldn’t be needed in this option, and the electronic circuit would be simplified.

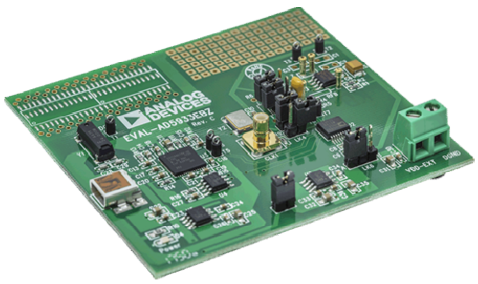


Figure 6. *AD5933 microcontroller (Source: <https://www.analog.com/en/design-center/evaluation-hardware-and-software/evaluation-boards-kits/eval-ad5933.html>)*

However, this option has some drawbacks too, such as the impossibility to create a computer-independent concept.

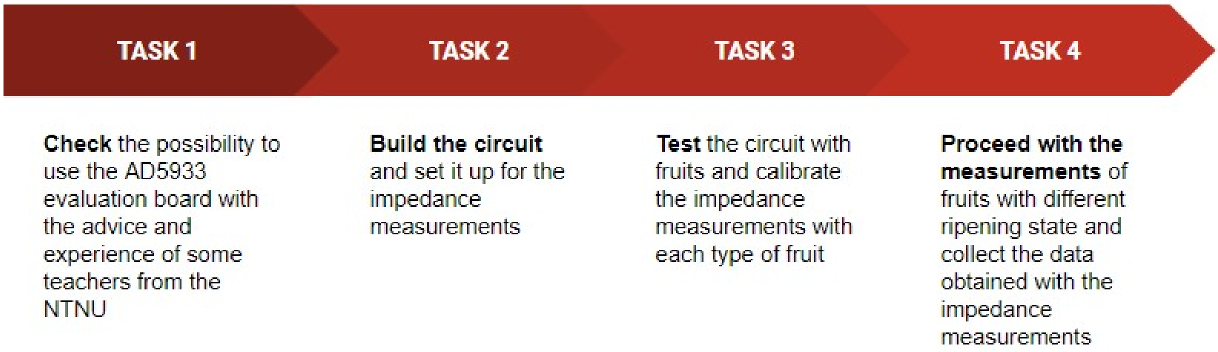
This leads us to the point that this option would be used to shorten the design work and focusing on the measurements themselves, so as to fully analyze the behaviour of the fruit’s electrical impedance during ripening and evaluate the possible relationship between the different results obtained and the ripening state of the fruit. Additionally, with this option, other parameters such as weight and visual aspect could be analyzed to obtain more complete information.

The following components would be needed to create this prototype:

- AD5933 board
- Electrical cables
- USB connection
- Laptop
- Electrodes

The following tasks for the construction of this concept would be:

Figure 7. *Tasks for the prototype with an AD5933 microprocessor*



2.5.3 Choice of the concept that will be built

In this section, the different characteristics of each option will be compared and the best one for the project's main goal will be chosen. In the previous sections, four different options have been analyzed.

The table below shows the main characteristics of each option:

Table 2. *Comparison between the prototypes*

Option 1: Existing prototype with colorimetry	• Price: 150€ • Measurable parameters: 2 • Accuracy of the measurements: Not very good concerning to previous usage • Laptop independence: yes
Option2: Existing prototype set up for other fruit	• Price: 3-12€ • Measurable parameters: 1 • Accuracy of the measurements: Not very good concerning to previous usage • Laptop independence: yes
Option3.1: New concept with AD5933 sensor	• Price: 50-70€ • Measurable parameters: 1 • Accuracy of the measurements: Very accurate, nearly as accurate as laboratory equipment. • Laptop independence: yes
Option3.2: New concept with AD5933 microcontroller	• Price: 50-70€ • Measurable parameters: 1 but other parameters could be measured with other techniques • Accuracy of the measurements: Very accurate, nearly as accurate as laboratory equipment. • Laptop independence: No

After analyzing these results we can first of all determine that, even though the price of each option is different, none of them are prohibitively expensive. Therefore, this factor will not influence the choice of the conceptual development.

Moreover, it is important to note that the main goal of the project is to obtain reliable data concerning the fruit ripening process and to establish a relationship between the measurements obtained and the ripening state of the fruit. The creation of a physical prototype is not the main goal, but rather to obtain reliable data.

Therefore, despite the fact that the first two options would represent a physical prototype they will be discarded, as the data obtained with their performance would not be reliable enough.

Consequently, only the two last options will now be considered. As we can see, these two options are quite similar, the only difference between them being that the AD5933 sensor board can’t be connected directly to a computer, meaning that an arduino would be needed, while the AD5933 microcontrolled-based board can be connected directly to a computer and controlled from it, as well as process and obtain the measurements, without the need of an arduino.

Despite the fact that with the AD5933 microcontrolled-based board it wouldn’t be possible to create a computer-independent concept, this option would allow us to shorten the design work and focus on the measurements. Moreover, with this option, other parameters such as weight and visual aspect could be analyzed so as to evaluate the relationship between the parameters and have more information about the fruit ripening process.

Therefore, it is considered that the **AD5933 microcontrolled-based board** would be the best option and the one that will be utilized.

3 RESEARCH AND ANALYSIS METHODS

3.1 LITERATURE STUDIES

In this project, literature studies have been necessary so as to acquire knowledge to understand the ripening process, as well as the different physical, chemical and biological parameters that intervene in this process. Moreover, literature has also been an excellent resource to study and obtain information about the different available techniques for determining fruit ripeness.

Most of the literature used for this project was obtained from the NTNU and UPC (Universitat Politècnica de Catalunya, Barcelona Tech) databases. Furthermore, the main reason for choosing these databases to obtain information is the reliability of the information that they provide.

Below is a table with both the research key words used to search data and the results obtained for each search:

Table 3. *Key words used during literature review*

Database	Key word used	Results obtained
NTNU Oria	Fruit ripening	65.474
NTNU Oria	Ripening destructive methods	3.897
NTNU Oria	Parameters fruit ripening	15.166
NTNU Oria	Ripening climacteric fruits	4.182
NTNU Oria	Fruit damage	213.739
NTNU Oria	Fruit mechanical damage	33.999
NTNU Oria	Fruit thermal damage	19.317
NTNU Oria	Ethylene fruit	39.232
NTNU Oria	Ethylene fruit ripening	15.982
NTNU Oria	Destructive techniques ripening	2.374
NTNU Oria	EIS ripening	892
NTNU Oria	Electrical impedance spectroscopy ripening	1.634
NTNU Oria	Bioimpedance fruit	529
NTNU Oria	Index of absorbance difference	75.146
NTNU Oria	IAD ripening	278
NTNU Oria	AD5933	235
UPC Bibliotècnia	Fruit ripening	28.546
UPC Bibliotècnia	EIS fruit	241
UPC Bibliotècnia	Maduración fruta	100
UPC Bibliotècnia	IAD fruit	85
UPC Bibliotècnia	AD5933	159

3.2 DATA COLLECTION

The data collection consisted of both quantitative and qualitative methods. The most important part of data was collected from an experimental research where both quantitative and qualitative methods were analyzed. The electrical impedance and the weight evolution were obtained as quantitative data. However, from the qualitative point of view, the visual appearance of the fruit was analyzed.

Therefore, the experiment was held over 12 days and the measurements were taken every morning at 1pm. The environment was a room mainly maintained at a temperature of 20ºC. The main aim of the experiment was to measure different parameters of three different types of fruits: bananas, mangoes and avocados. Eight examples of each fruit were used for the experiment and they were kept at room temperature during the experimenting days. The parameters measured and analyzed were the electrical impedance and phase, the weight and the visual appearance, in the order specified.

3.3 STATISTICAL METHODS OF ANALYSIS

Several statistical methods were used to analyze the results obtained with the experiments.

On one hand, dispersion charts were used to analyze the weight evolution throughout the ripening process and the relationship between the weight and the fruit's impedance.

On the other hand, a big part of the statistical analysis was made through box plots. These kinds of charts give visual information about how the data is distributed. Moreover, they also give information about:

- The maximum and minimum data points.
- Mean value and median.
- Standard deviation and dispersion of the data.
- Outliners: Data points which are numerically distant from the rest of data

Below, the formula of the mean value and the standard deviation is attached:

$$\boldsymbol{Mean\ value\ \bar{X} = \frac{\sum_{i=1}^{n} Xi}{n}}$$

$$\boldsymbol{Standart\ deviation\ SD = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{X})^2}{n}}}$$

(Source: Ronald E.walpole et al., 2007)

Therefore, the data was graphically represented with these methods mentioned and the analysis was based on the charts obtained.

3.4 TOOLS USED IN THE RESEARCH

Different tools and materials were used to obtain data for the experiment. Weights were measured on simple, but accurate, kitchen scales and visual appearances were captured on an iPhone Xs camera. Colour evaluations were obtained using “imagej” software.

The electrical impedance readings were calculated and measured using an electronic circuit built on an AD5933 board. Other materials employed include contact pads and electrical cables. Additionally, the data was processed thanks to the AD5933 board software.

Finally, Microsoft Excel software was used to process and analyze the data.

4 EXPERIMENT AND RESULTS

4.1 EXPERIMENTAL CIRCUIT

In this section the different components that made up the electronic circuit will be specified and determined, and the final experimental setup of the project will be defined.

4.1.1 Components

After lengthy research into the several options that could have been used to create the experimental circuit, the devices that were chosen are specified in this section:

4.1.1.1 Analogical devices

As has already been specified in the previous section, the experimental setup consisted mainly of a microcontroller-based AD5933 board.

This impedance analyser was obtained from the company “Analog Devices”, who provide a fully featured evaluation board for the AD5933 impedance analyser sensor and graphic user interface software with frequency sweep capability for board control and data analysis (Analog devices, Data sheet, 2005).

4.1.1.2 Electrodes

After extensive research and some literature review, it was determined that the best electrodes that could be used to measure electrical impedance are Silver/Silver Chloride ECG electrodes (Ag/AgCl ECG electrodes).

These kinds of electrodes have a solid-gel conductive adhesive that ensures reliable recordings and that will stick to the skin of the fruit. They are disposable, which means that they can be thrown away after single usage and replaced by new ones for the next set of measurements.

4.1.1.3 Electrical cables

Two different kinds of electrical cables were needed to create the electronic circuit: jumpers and USB connection cable.

- Firstly, two double-ended alligator jumpers were needed to connect the electrodes to the AD5933 board.
- Secondly, a USB cable capable of connecting the AD5933 board to the computer.

Figure 8. *Double-ended alligator cables (Source: <https://www.olelectronics.com/product/double-ended-alligator-clips-test-lead-jumper-wire-pack-of-10/>)*

4.1.1.4 Fruit

As was stated at the very beginning of the report, climacteric fruits were analysed rather than non-climacteric fruits, as these can still ripen after harvesting. However, there are different types of climacteric fruits that could have been used for the purpose of this project.

Following some literature review and after analysing the different aspects that could be measured, it was decided that the most suitable fruits for the project were avocados, mangoes and bananas.

The main aspects that were considered for this choice are:

- All these fruits have different structures and it would be interesting to analyse the results obtained and compare them.
- They change their aspect and colour during the ripening status, so it would be very interesting to relate each ripening status with the visual appearance.
- Because of the different geometry of these fruits, the variation of results obtained thanks to various different dispositions of the electrodes could be analysed.

4.1.2 Final setup

In the following illustration the electronic circuit setup of the project is displayed. Also, the different components that were used are specified.

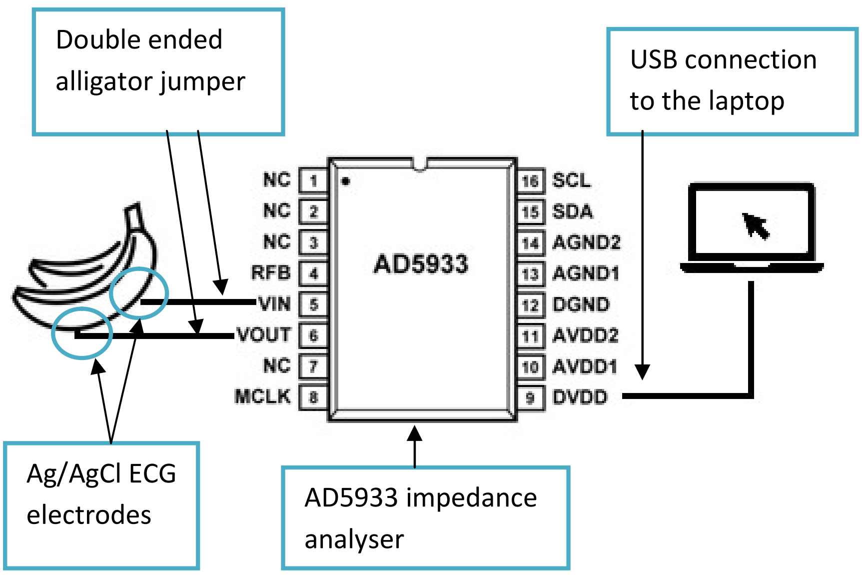


Figure 9. *Experimental electronic circuit (Source: AD5933 Data Sheet. 2005)*

This leads us to the stage where we are already able to study the experimental design and the different procedures that were carried out to collect the data.

4.2 PRE-EXPERIMENT MEASUREMENTS AND TRY-OUTS

Before starting with the experiment, the AD5933 board had to be tested and the results obtained had to undergo analysis to determine whether they were reliable enough or not. Therefore, as soon as we had the AD5933 board, different experiments and try-outs were made in order to check the performance of the board. However, several problems had to be faced during this process, which will be explained in this section.

4.2.1 Calibration problems

After lengthy research into the performance of the AD5933 board, it was proved that calibration was needed before getting any reliable data from the impedance analyzer and therefore, also before plugging an unknown resistance (e.g. fruit).

To do so, two resistors had to be plugged in the board: both the resistor called Zunknown and the feedback resistor, called RFB (Analog Devices, Data Sheet. 2005). For this calibration state, it was needed to know the resistance values of each of these resistors that we wanted to plug.

The Zunknown was the one that the board could evaluate, as well as the one that the software could inform about the value of the resistance plugged in this place (Analog Devices, Data Sheet. 2005). Therefore, in this calibration state, as the value of the resistor connected to Zunknown plug was known, the software would have to show the same value of resistance that is connected, and that we already know (Riorda, Liam, 2012).

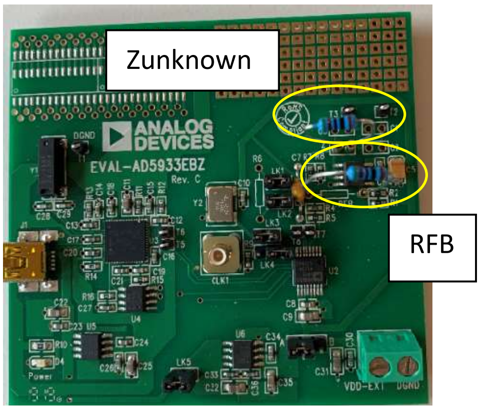


Figure 10. *Zunknoun and RFB resistors during calibration routine with 510 Ω resistors*

Therefore, to calibrate the board, two resistors were connected with the following values:

- Zunknown= 100 kΩ
- RFB= 220 Ω

However, the board miscalculated the value and the software indicated that the value of the Zunknown resistance was 1,25E-5Ω, instead of 100kΩ, which lead us to the conclusion that something was not working properly.

Furthermore, it was noticed that the software set up during the calibration was incorrect. The Mid-Point Frequency calibration setting was used instead of the Multi

Point Frequency calibration setting, which lead to incorrect measurements. However, after changing this setting, the board and the software were capable of showing the right value of resistor that was plugged in.

Moreover, to have a fully understanding of the board, its circuit was also analyzed:

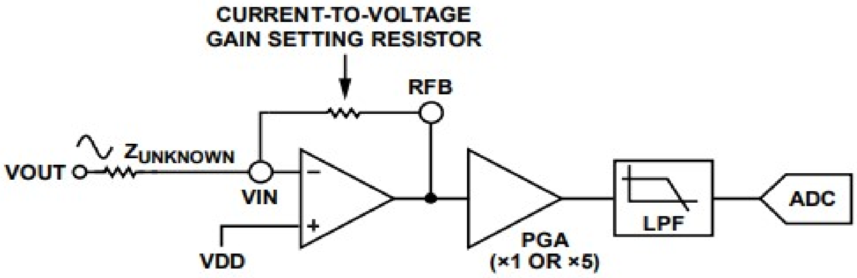


Figure 11. *AD5933 System Voltage Gain (Source: AD5933 Data sheet. 2005)*

As is shown in the picture, the Zunknown and the feedback resistor are related through an operational amplifier, and these devices can work within a range of values. Therefore, it was thought that using the same values of resistors would be a good idea to have less parameters to control.

This is the reason why afterwards, two resistors with the same exact value were used to calibrate the board and the software could successfully calculate the right value of the plugged resistance, meaning that the board was then successfully calibrated.

It is important to remark that this calibration routine was necessary before taking any measurements.

The following picture shows both the settings that were set for the calibration routine of a 510 Ω resistor and the results obtained with the board:

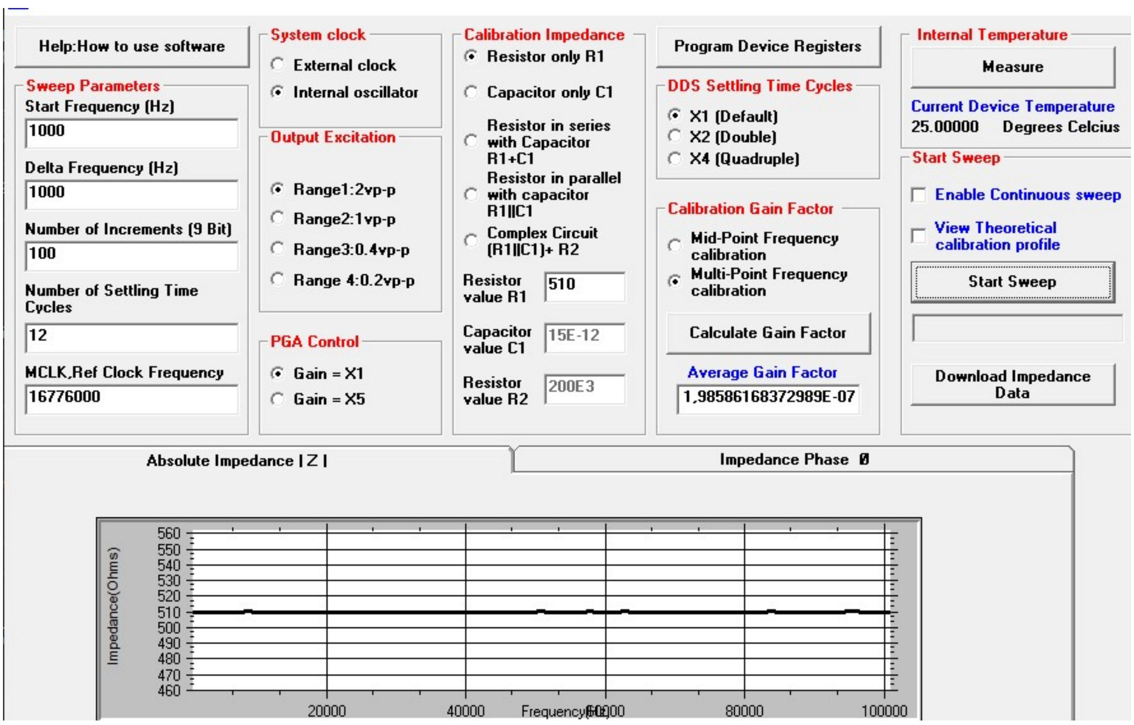


Figure 12. *Calibration routine and its settings with a 510 Ω resistor (Source: Screenshot of the AD5933 software)*

4.2.2 Try outs with different calibration resistors and fruit

As mentioned in the previous section, two resistors are needed to go under calibration routine and both are supposed to be the same value.

However, it was proved that the AD5933 board showed different values of fruit impedance when calculating this value with different calibration resistors.

This is the main reason why some pre-experimental measurements were made before starting the final experiment. In these measurements, one banana, one mango and one avocado were used to obtain results that could tell which calibration resistors values were the ones that showed better impedance variation throughout the days.

In the following table, the impedance peak value obtained for each fruit with different resistors is showed.

Table 4. *Try outs with different values of resistors and the impedance peak value obtained*

RESISTORS	FRUIT	06/05/2020	07/05/2020	08/05/2020
510 Ω	Banana	19449,9 Ω	19351,51 Ω	18966,53 Ω
	Mango	44996,92 Ω	33792,84 Ω	31214,59 Ω
	Avocado	18481,719 Ω	13717,14 Ω	10399,17 Ω
1k Ω	Banana	3686,033 Ω	3763,14 Ω	3719,80 Ω
	Mango	20183,46 Ω	7537,13 Ω	7177,49 Ω
	Avocado	4322,46 Ω	3164,06 Ω	2436,66 Ω
51k Ω	Banana	32011,38 Ω	32164,53 Ω	32758,78 Ω
	Mango	42583,77 Ω	39759,69 Ω	39786,07 Ω
	Avocado	34311,66 Ω	35447,17 Ω	34776,05 Ω
100k Ω	Banana	62574,35 Ω	62426,2 Ω	63219,65 Ω
	Mango	64193,44 Ω	62760,81 Ω	63218,33 Ω
	Avocado	48539,64 Ω	48747,77 Ω	68908,66 Ω
300k Ω	Banana	204453,18 Ω	203264,22 Ω	201513,29 Ω
	Mango	185970,32 Ω	193629,92 Ω	192627,22 Ω
	Avocado	204804,74 Ω	212308,3 Ω	208505,98 Ω
470k Ω	Banana	325780,22 Ω	329959,13 Ω	320779,06 Ω
	Mango	300883,59 Ω	313180,46 Ω	312200,92 Ω
	Avocado	334856 Ω	335639 Ω	329991,28 Ω
680k Ω	Banana	485226,28 Ω	485171'52 Ω	487384,57 Ω
	Mango	454420,29 Ω	467516,44 Ω	469445,08 Ω
	Avocado	489233,21 Ω	493053,32 Ω	480651,25 Ω

4.2.3 Calibration resistor choice

Having a look at the Table 4, we can see that the results obtained with different resistors show that the lower the resistor value is, the higher is the variation throughout the days.

This is the reason why a 510 Ω resistor was chosen for the calibration routine that was used for the final experimental measurements, as this value was the one that showed a better impedance variation.

4.3 EXPERIMENTAL DESIGN AND DATA COLLECTION

4.3.1 Experimental environment

The experimental measurements all took place in a room maintained at an average temperature of 20 degrees. The fruit was kept in this room at all times throughout the experimentation period, keeping it stable and avoiding external influences affecting the ripening parameters. The measurements were carried out every morning at 1 pm for a period of **12 days.**

Finally, the fruits were placed on a wooden table when being analyzed, as shown in the following picture:

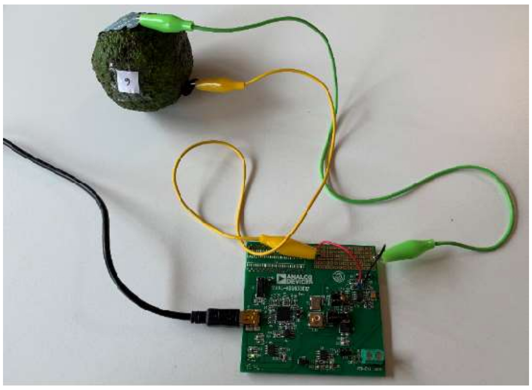


Figure 13. *Experimental set up during the measurements of an avocado*

4.3.2 Fruit condition

The fruit that was used for the experiment was bought in a supermarket in an unripe state. As previously stated, mangoes, bananas and avocados were used for this experiment:

- A selection of unripe bananas, mangoes and avocados was chosen.
- The experiment measured the parameters of **8 examples** of each fruit.
- Each piece of fruit was enumerated with a label, so as to be able to identify them day-to-day.

Figure 14. *Unripe fruit aspect on the first day of measurements and avocados with the identifying lables*

4.3.3 Data measurements

Since we are aiming to analyse as many parameters as possible in order to obtain reliable data about the fruit ripening process, three different parameters were analysed and measured in this experimental design: electrical impedance, weight and colour.

4.3.3.1 Electrical impedance spectrometry

In this section, the experimental process that was followed is attached, containing information about the settings used for the measurements of the fruit's impedance.

First of all, in the following picture you can find the settings used for the measurements of the electrical impedance and phase:

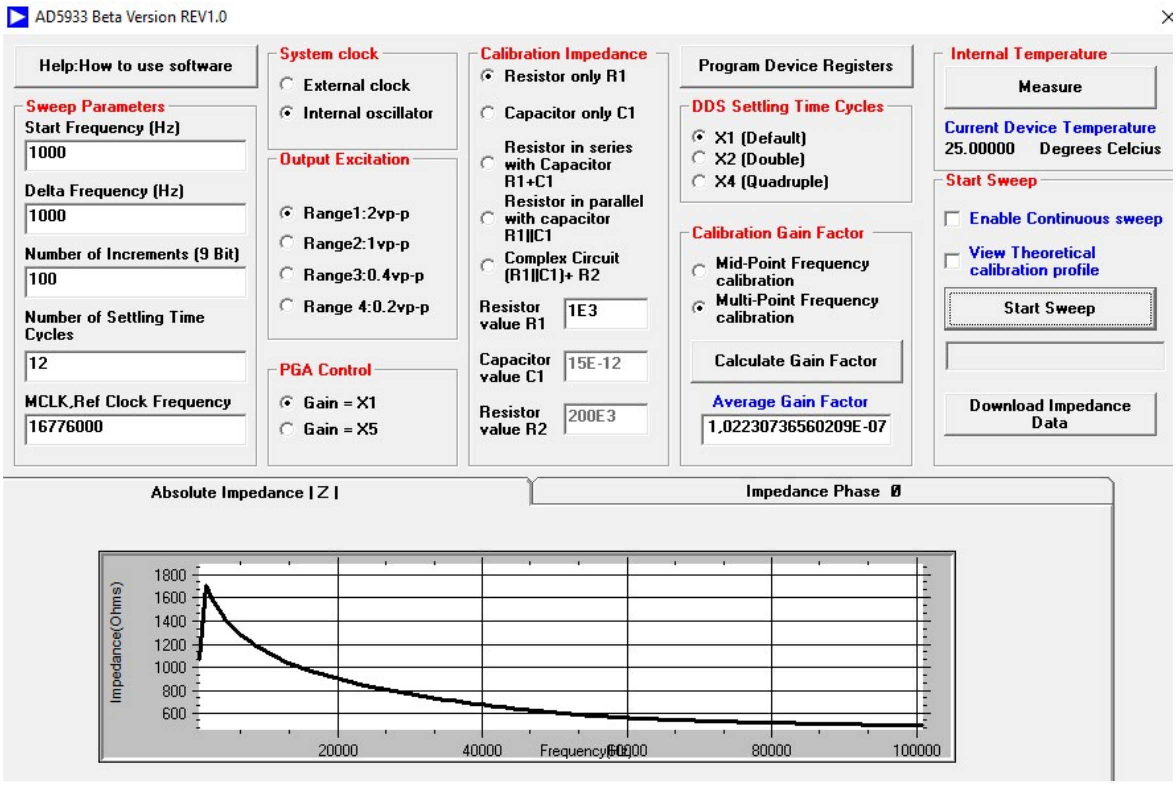


Figure 15. Software settings during impedance measurements (Source: Screenshot of the AD5933 software).

As is shown, the parameters used were:

- Frequency swipe applied: *From 1000 Hz to 100.000 Hz*
- System clock: *Internal oscillator*
- Excitation voltage: *2 Volts*
- Calibration resistor: *510Ω*
- DDS settling time cycles: *X1*
- Calibration Gain Factor: *Multi-Point Frequency calibration*

Moreover, it is important to remark that the impedance measurements were taken every day at 1 pm and that the data was processed with excel.

4.3.3.2 Sensitivity Analysis

The sensitivity analysis of the measurements was obtained by comparing the results obtained with measurements that were made with different positions of electrodes during three different days of analysis: Day 2, 7 and 12.

Therefore, two different positions of electrodes were placed on the skin of the banana nº4, avocado nº2 and mango nº3: the first position was the same one that was used during all the experiment and the other one was completely different.

The following pictures show both the standard position and the different position of electrodes:

Figure 16. Mangos sensitivity analysis. *Left picture: Other position of measurements; Central picture: Normal position, front view; Right picture: Normal position, back view.*

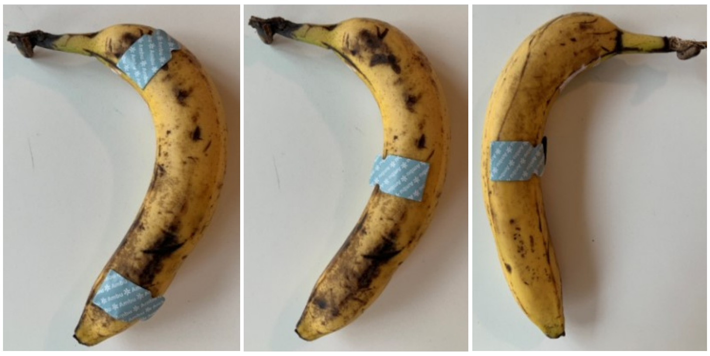


Figure 17. Bananas sensitivity analysis. *Left picture: Normal position of measurements; Central picture: Other position, front view; Right picture: Other position, back view.*

Figure 18. Avocados sensitivity analysis. *Left picture: Other position of measurements; Central picture: Normal position, front view; Right picture: Normal position, back view.*

This task was done so as to check the sensitivity of the measurements with different position of the electrodes.

4.3.3.3 Weight

The weight was measured using accurate kitchen scales in order to evaluate the change of this parameter throughout the ripening process with the different fruits. Moreover, this magnitude was measured every second day and the results were recorded in an excel sheet.

4.3.3.4 Colour

The colour of each fruit was evaluated every second day. A picture of one example of each fruit was taken with an Iphone Xs camera using natural light. The chosen fruits to take measure this parameter were:

- Banana nº1
- Avocado nº1
- Mango nº1

Following this, the colour composition of the whole image was evaluated using Fiji software. However, as this software only provides the digital number of red, green and blue, the different percentages of these were calculated:

$$Total\ Digital\ Number = Red\ DN + Green\ DN + Blue\ DN$$

$$Red\ \% = \frac{Red}{Total\ DN} x100$$

$$Green\ \% = \frac{Green\ DN}{Total\ DN} x100$$

$$Blue\ \% = \frac{Blue\ DN}{Total\ DN} x100$$

Where DN stands for “Digital Number”, which value is provided with the Fiji software. In this way, the evolution of the colours of the fruit were analyzed and compared.

4.4 EXPERIMENTAL RESULTS

In this section, all the results that were obtained with the experimental measurements are shown. Therefore, the weight, the electrical impedance and the phase angle evolutions are attached, as well as the relationship obtained between all the measurements taken between the fruit samples. Moreover, the mathematical tendency of some of the results is explained as well, showing graphically the mean value and the standard deviation.

On the other hand, an assessment between the colour evolution of the fruits is also included, as well as the relationship between weight and electrical impedance spectrometry.

Moreover, the results obtained from the sensitivity analysis are also included, showing how a different disposition of electrodes can affect the results.

Finally, I would like to highlight that the results of impedance and phase of day 8 show an odd behaviour in comparison with the overall behaviour of the magnitudes analyzed. Therefore, it is believed that something went wrong during day's 8 measurements. However, the reasons of such behaviour are unknown.

4.4.1 Weight evolution

In this part of the experimental results, the weight evolution between the different samples of the bananas, mangoes and avocadoes is shown.

In the following three charts, it can be observed how the weight evolution of each banana, mango and avocado follows a really linear decreasing evolution, meaning that the weight loss for each piece of fruit is constant and linear.

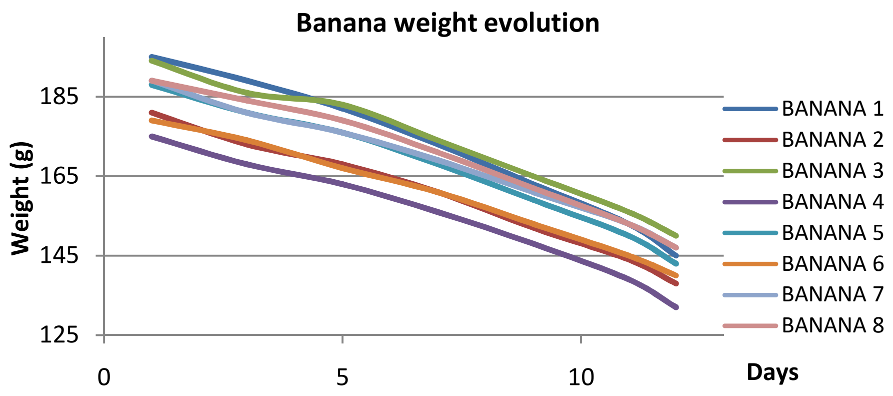


Figure 19. *Bananas weight evolution*

As we can see, the slopes of the weight evolution lines of each banana are very similar, following the same tendency to decrease.

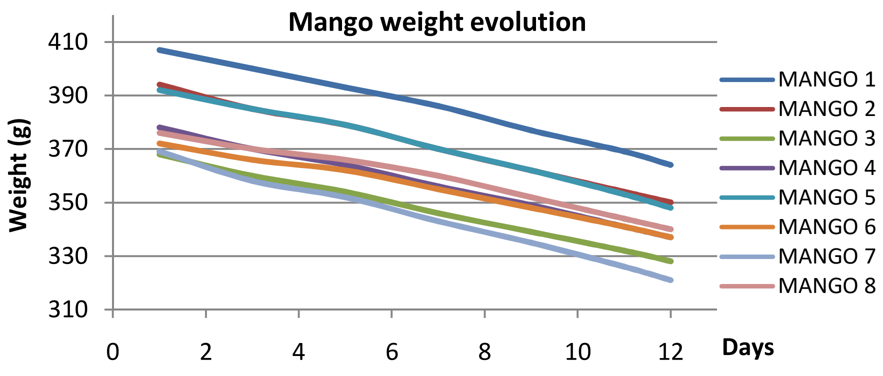


Figure 20. *Mangos weight ervolution*

Equivalent to banana, it is noticeable that the slopes of the weight evolution lines of each mango are also nearly the same, following a linear decrease.

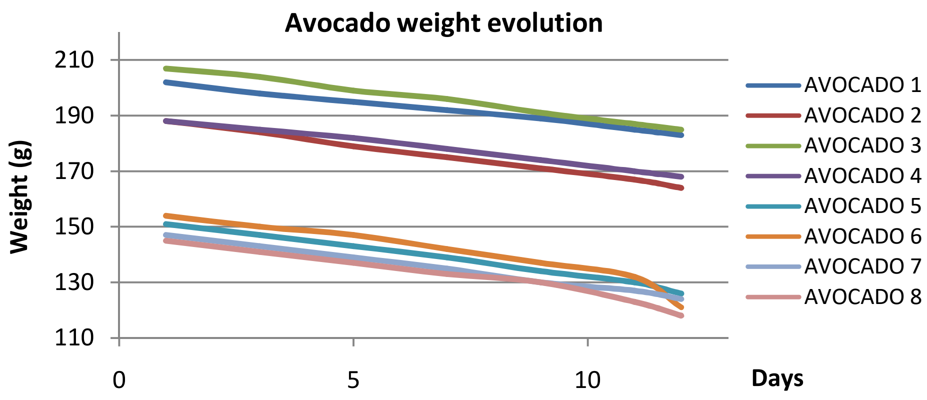


Figure 21. *Avocados weight evolution*

Finally, and equally to the last results, we can see that the slopes of the evolution lines of avocados is nearly the same as well.

Thanks to these three charts, we can conclude that the weight evolution all of the three fruits follows a linear decreasing evolution, meaning that the weight loss for each piece of fruit is more or less constant and linear, following similar mathematical slopes. Nevertheless, this doesn't give information about whether each kind of fruit is losing the same percentage of weight, independent to the original weight.

This observation leads us to the point that a statistical study could be made so as to determine whether fruits daily loss the same percentage of weight independently of their original weight.

To do so, the weight loss percentage was calculated. This value was obtained as the difference between the weight of the day of study and the weight obtained two days before, divided by the original weight. Herein, you will find the equation that was used:

$$Weight\ loss\ Day\ 5\ (\%) = \frac{Day\ 5\ Weight - Day\ 3\ Weight}{Original\ Weight\ (Day\ 1\ Weight)} * 100$$

The results obtained for all the examples of all the fruits were evaluated under a box plot analysis between the experimental days and the weight loss percentage [See section number 3.3 for more information about the statistical analysis]. Therefore, the main reason for choosing this kind of analysis is so as to be able to determine graphically the behaviour of the fruit and obtain information about the mean values and the standard deviation between all the data.

In the three following charts we can see the box plot of these mentioned parameters for each type of fruit.

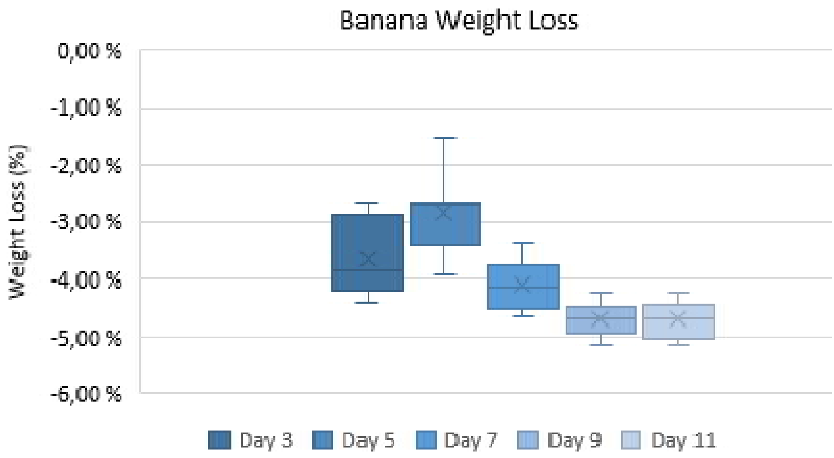


Figure 22. *Banana weight loss*

As we can see from the chart, the weight loss from day to day of all bananas is not constant:

- As the chart shows, the mean value is not constant during the period of time from day 3 to day 7, while during the period of time from day 9 to 11 is constant.
- Moreover, we can appreciate that the standard deviation among days is also different, as the length of the boxes varies: Day nº3 has the highest standard deviation, meaning that the dispersion of all the different data points (the different bananas weight) is higher. Nevertheless, this dispersion is lower on the following days, being quite low on the last two days.
- Finally, the box plot of day nº 5 is considerably higher than the rest of the days, meaning that the day to day weight lost of day nº5 is higher than the rest of the groups. However, days nº 9 and 11 show the lower box plot, meaning that the day to day weight lost of those days is lower than the rest of the days.

From these results, we can conclude that during the last few days, and therefore in the riper state, all the bananas were losing the same percentage of weight, independently of their original weight, while in an unripe state (first few days), weight loss is more dependent on the original weight of each fruit, as the dispersion between samples is higher. Therefore, we can conclude that the weight loss from day-to-day is not constant for bananas.

In the following chart, the box plot of mangoes day- to- day weight loss is displayed:

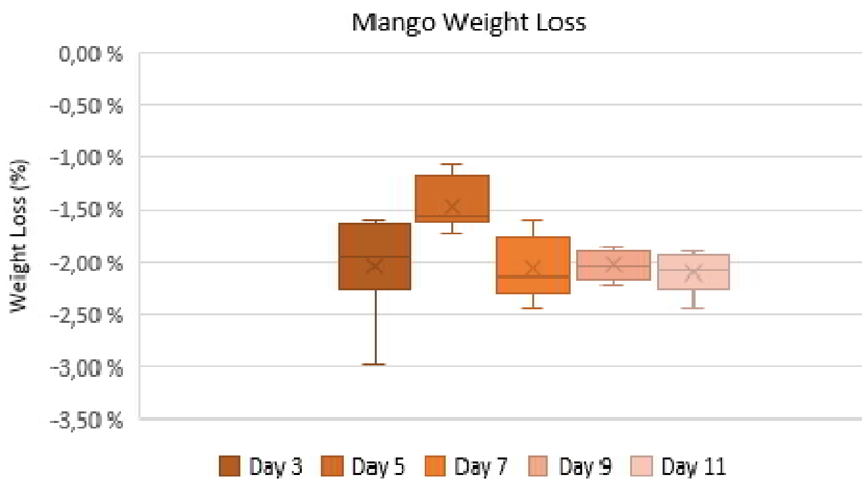


Figure 23. *Mango weight loss*

Equivalent to the results obtained with the bananas, we can see that the mangoes day-to-day weight loss is quite similar to the banana one:

- The dispersion of the results follows the same behavior as the bananas, while the mean value evolves differently.
- We can appreciate that on day nº 3, 7, 8 and 9 the mean values are quite similar. Nevertheless, it is important to remark that even though these means are at the same level, the dispersion of the results varies, being way higher on days nº3 and 7 than on days nº9 and 11.
- Contrary to this behavior, we can appreciate that on day nº5 both the mean and the box plot are higher, meaning that the day-to-day weight lost of day nº5 is higher than the rest of the days.

With these results, we can conclude that in a riper state (last few days) all mangoes were losing the same percentage of weight, independently of their original weight, while in an unripe state (first few days), weight loss is more dependent on the original weight of each fruit, as the dispersion between samples is higher.

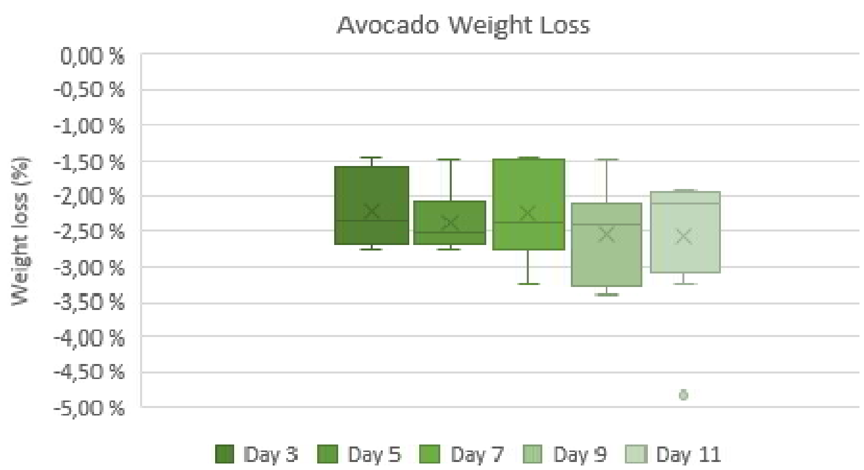


Figure 24. *Avocado weight loss*

Finally, the box plot above shows that the mean value of the day-to-day weight loss of avocados is even and the boxes are more or less at the same height, which leads us to the conclusion that the day-to-day weight loss is quite similar and therefore, constant. However, we can appreciate that each day's standard deviation is higher than the one obtained with bananas and mangoes.

4.4.2 Electrical impedance evolution

In this section of the experimental results, the fruit's electrical impedance evolution throughout the experimental days is evaluated.

As previously stated, the fruit's electrical impedance is frequency-dependent and this statement can be corroborated with the results obtained below.

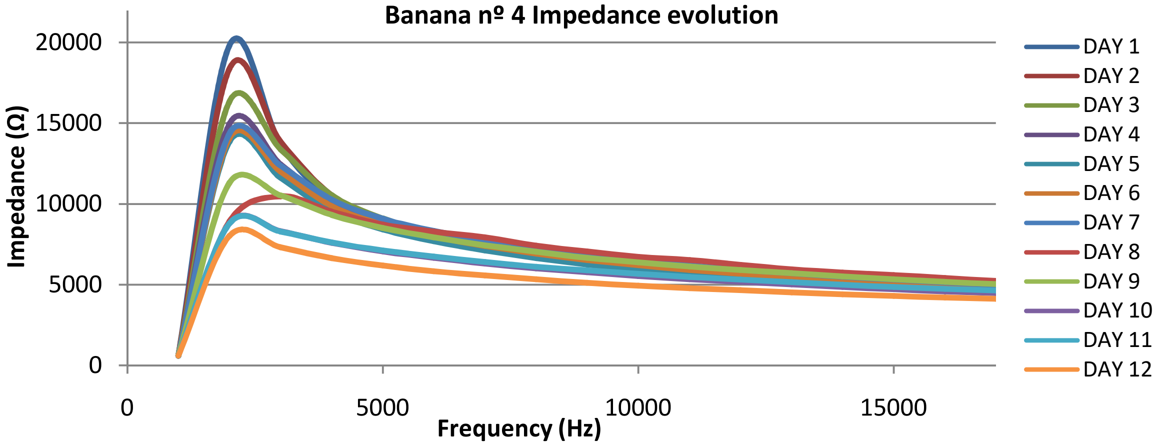


Figure 25 *Example of a Banana's impedance evolution during frequency swap throughout 12 ripening days*

As we can see, for this example of banana, the impedance varies throughout the frequency swipe, obtaining the peak value of impedance at the frequency of 2000 Hz and consecutively falling down and stabilizing at the value of 5000 Ohm. Furthermore, we can observe how all the measurements stabilize after the peak value at the same value of impedance, without regarding the day of ripening.

Moreover, as we can observe, the impedance value decreases throughout the different ripening days, obtaining the highest value of impedance on the first day of measurements and the lowest on the last day. Although the chart attached above only shows the impedance evolution of one example of banana, this behaviour described was followed by all of them.

Below, a box plot of the evolution of the peak value of impedance of all bananas is displayed:

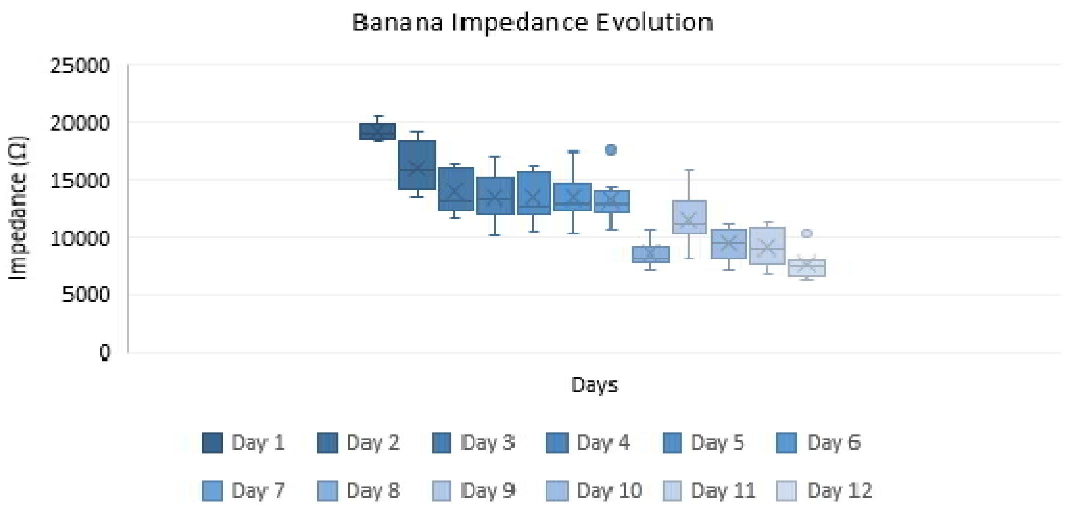


Figure 26. *Banana impedance evolution*

As we can see, the impedance of bananas follows a decreasing behaviour during ripening.

- The mean value follows a decreasing behaviour throughout all the days, with the exception from day 8 to 9, where it increases.
- Moreover, we can appreciate that the standard deviation of the set of impedance measurements is quite low, meaning that the dispersion of the different measurements is quite low and close to the mean value.
- Furthermore, it is important to highlight that the results show how bananas in a very unripe state have a very low standard deviation (Day 1), and this same phenomena happens when they are very ripe (Day 12), meaning that all of the bananas show very similar values at these stages.
- Finally, as has already been stated, we can see that the impedance on day 8 falls considerably. The reasons of such behaviour are unknown.

Therefore, we can conclude that bananas exhibit lower values of impedance as they ripen.

Following the same analysis as the bananas impedance evolution, the following chart shows the results obtained with the electrical impedance spectrometry of avocadoes.

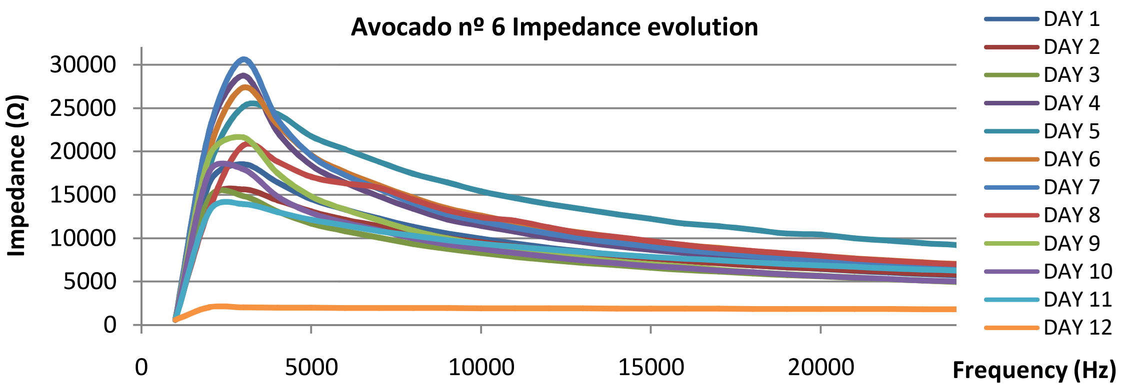


Figure 27. *Example of an Avocado's impedance evolution during frequency swap throughout 12 ripening days*

As we can see, the avocado impedance also varies throughout the frequency swipe, obtaining the peak value of impedance at the frequency of 3000 Hz and consecutively falling down and stabilizing around the value of 5000 Ohm.

However, as we can observe, contrary to the banana's results, the avocado's impedance value doesn't follow the same decreasing pattern throughout the different ripening days. Moreover, the impedance behaviour from all of the avocadoes was quite different.

In the following box plot we can see the avocado's impedance peak value evolution:

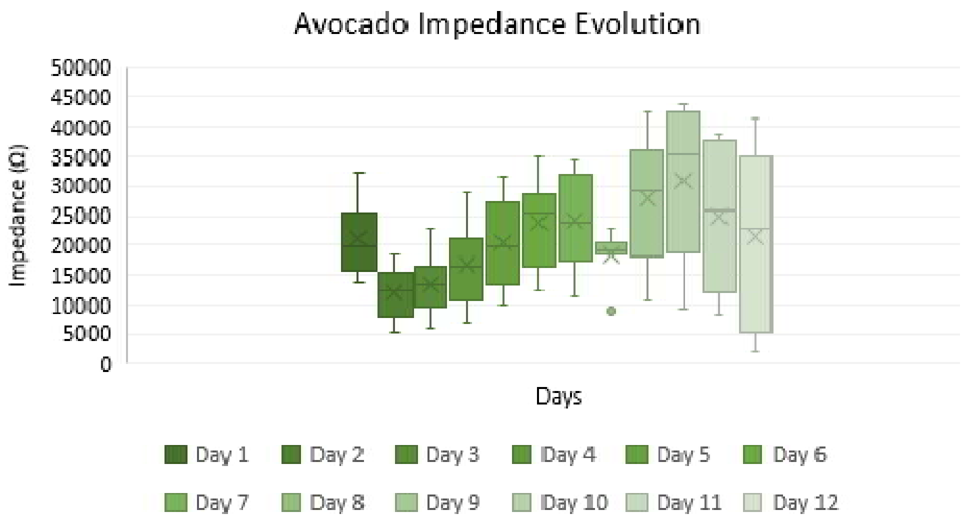


Figure 28. *Avocado Impedance Evolution*

As we can see, the evolution of the avocados impedance follows an irregular behaviour:

- The mean value decreases from day 1 to day 2, from day 7 to day 8 and from day 10 to day 12. However, it increases from day 2 to day 6 and from day 9 to 10. Therefore, we can see that the mean value doesn't follow any pattern.
- Moreover, we can see that the standard deviation is quite high every day and even higher on the last days. This means that each day's variation of the set of impedance is high and disperse and therefore that the impedance behaviour among all of the avocadoes was quite different.

This leads us to the conclusion that we are not capable of determining the tendency of the avocado impedance during ripening, as the data obtained is too disperse and the tendency too irregular.

Finally, and to end this section, the following charts show the results obtained with the mangoes impedance analysis.

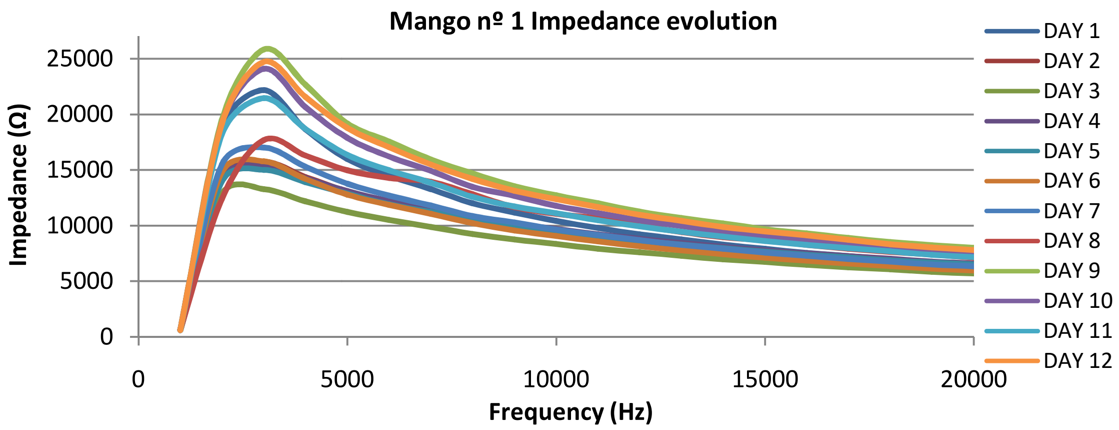


Figure 29. *Example of a Mango's impedance evolution during frequency swap throughout 12 ripening days*

As is shown in the chart, mangoes follow the same impedance behaviour towards the frequency swipe: the impedance values reach the peak value at the frequency of 3000Hz while they also consecutively stabilize around the impedance value of 5000 Ohm.

However, the box plot below shows that unlike the bananas, the mangoes show an increasing tendency of impedance throughout the ripening days.

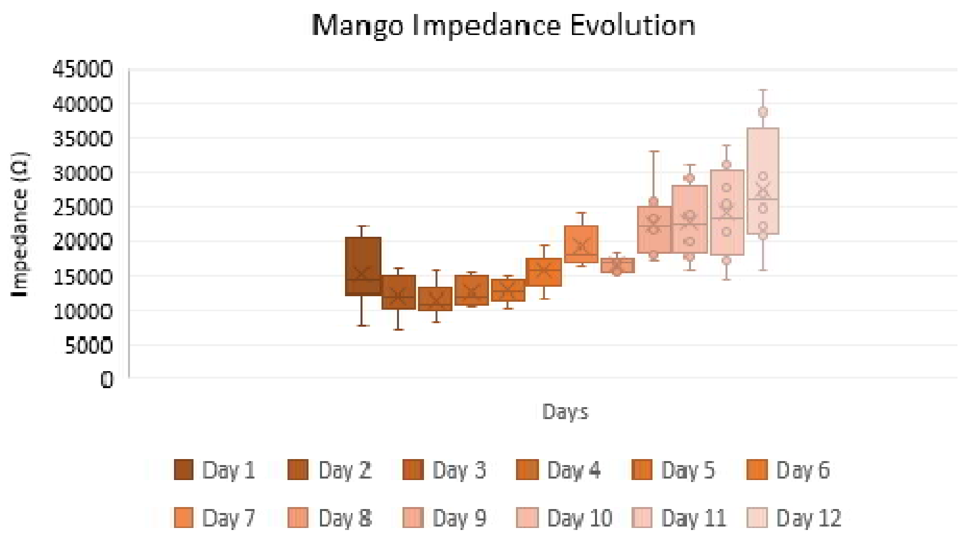


Figure 30. *Mango impedance evolution*

As the chart shows, even though during the first three days the mangoes show a decreasing tendency of impedance, during the following days this value increases significantly. Furthermore, we can see that the mean value follows the same behavior.

On the other hand, we can also appreciate that the standard deviation of the set of data increases as the mangoes ripen, meaning that in this stage the set of analyzed mangoes show different results. Finally, we can conclude that the impedance of mangoes increases when these fruits ripen.

4.4.3 Phase evolution

As has already been stated in previous sections, the fruit's bio-impedance presents both a real and imaginary part, meaning that the phase is the other important parameter of impedance measurements, besides the impedance module. Therefore, in this section the fruit's phase evolution throughout the experimental days is evaluated.

Equally to impedance evolution, we can see that the phase is frequency-dependent too. Therefore, the following charts show the evolution of impedance throughout a frequency swipe for the three types of fruits.

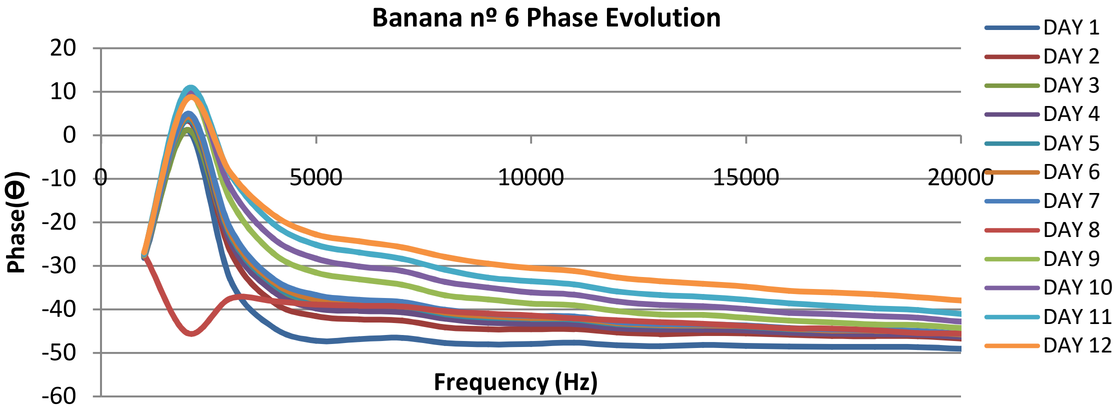


Figure 31. *Example of a Banana's phase evolution during frequency swap throughout 12 ripening days*

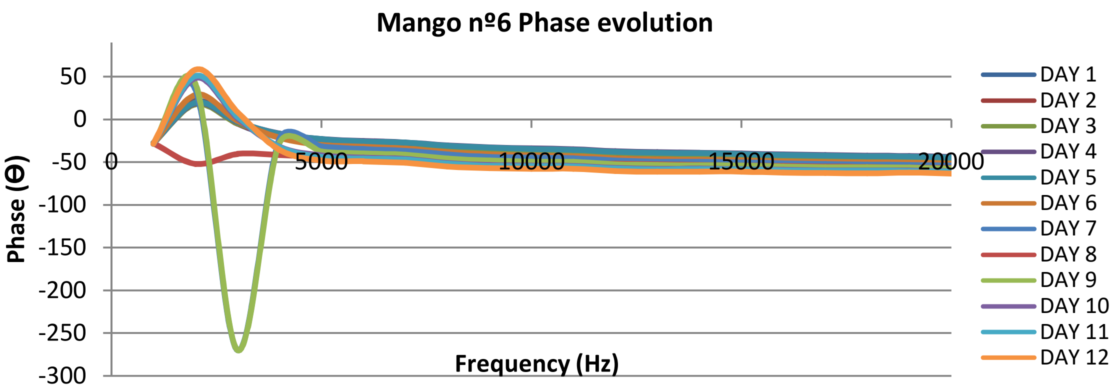


Figure 32. *Example of a Mango's phase evolution during frequency swap throughout 12 ripening days*

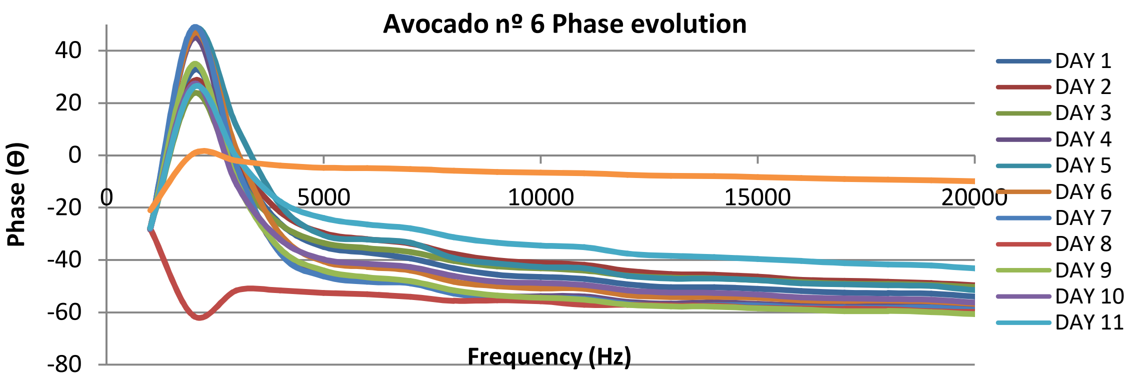


Figure 33. *Example of an Avocado's phase evolution during frequency swap throughout 12 ripening days*

The previous charts showed that the phase angle stays nearly stable throughout the ripening stages, even though we can also notice some peaks and exceptions to the general behaviour. However, three box plots are included below to compare these values with all the set of data of each fruit.

It is important to highlight that the peak values were the ones used to make the box plot analysis.

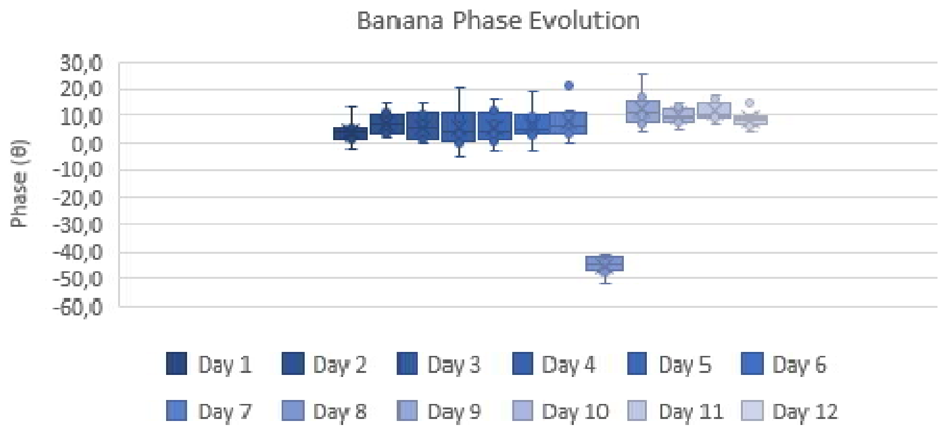


Figure 34. *Banana phase evolution*

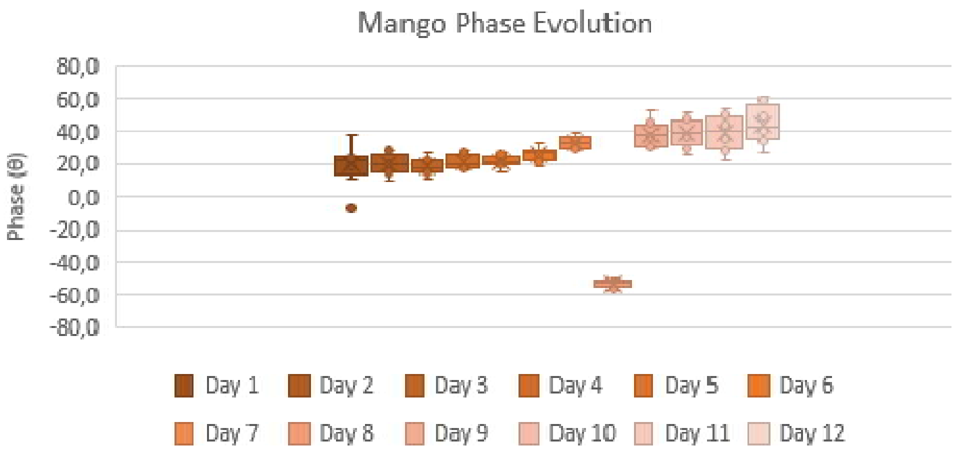


Figure 35. *Mango phase evolution*

As we can appreciate, the two box plots above show a similar behaviour:

- The mean values remain at the same level, but they increase slightly on the final days.
- The standard deviation is quite low on every day, meaning that the spread of the different sets of data is low. However, it increases during the ripening stages for the mango.
- We can also appreciate the existence of outliners, as the charts show data points which are numerically distant from the rest of data.

Furthermore, the chart below shows the avocados' phase evolution:

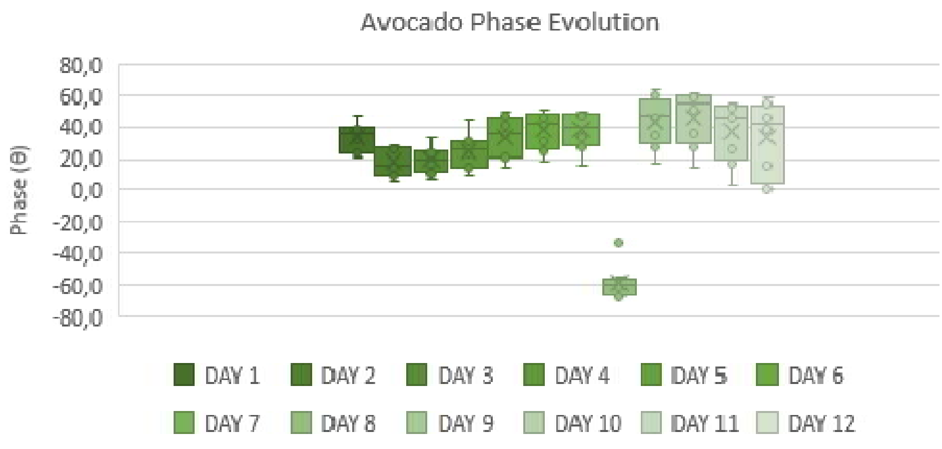


Figure 36. *Avocado phase evolution*

Contrary to the behaviour described in the two previous charts, the avocado shows a higher spread of data and irregular tendency of the mean value.

An important aspect to highlight is that the three charts show the same behaviour on the day 8 of analysis: there is a huge decrease of the phase value compared to the other days. However, as stated at the beginning of this section, the reason for this behaviour remains unknown.

As an overall analysis, we can appreciate that there isn't a significant tendency of the fruit phase when ripening, meaning that the angle stays constant and without giving important information about the fruit ripening process.

4.4.4 Colour evolution and visual aspect

In this section, the visual appearance of the fruit is evaluated and the colour composition is analysed thanks to the colour analyzer software called Fiji. This application was used to obtain the composition of red, blue and green from the fruit pictures. However, these values were given with a colour digital number, which lead us to the point that the colour percentage was needed to be calculated. As was explained before, these percentages were obtained like:

$$Total\ Digital\ Number = Red\ DN + Green\ DN + Blue\ DN$$

$$Red\ \% = \frac{Red\ DN}{Total\ DN} x100$$

$$Green\ \% = \frac{Green\ DN}{Total\ DN} x100$$

$$Blue\ \% = \frac{Blue\ DN}{Total\ DN} x100$$

Where DN stands for "Digital Number".

In the following three charts, the colour percentage evolution of each type of fruit is represented.

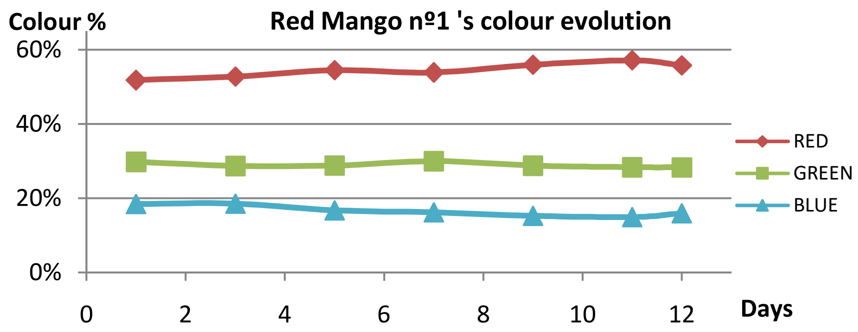


Figure 37. *Mango color evolution*

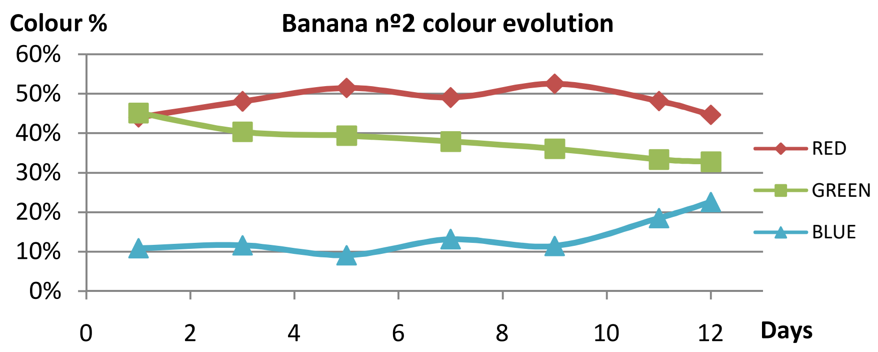


Figure 38. *Bananas color evolution*

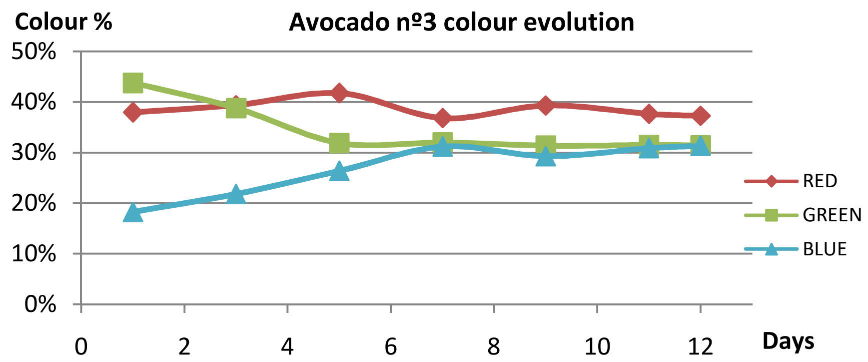


Figure 39. *Avocado colour evolution*

By analysing the charts, different behaviours can be appreciated. Firstly, the mango fruit doesn't seem to show any significant variation of the colour composition during the ripening stages, following nearly a linear behaviour.

Nevertheless, despite the fact that the banana follows the same behaviour during the 5 first days of analysis, this fruits shows some variations during the following days: the red and green percentages decrease while the blue increases.

Finally, the avocado shows an increase of red and blue and a decrease of green during the first 6 days, but afterwards this behaviour stabilizes and there is no significant variation during this last period of time.

Therefore, in general, this analysis shows that there is not a huge or significant variation of colour composition throughout the ripening days with this colour evaluation with the Fiji software.

However, the following pictures show the visual state of the fruit on the very first and last days of measurements:

Figure 40. *Fruit aspect on the first and last days of measurements*

Therefore, with these two pictures, we can see that the colour variation is obvious and can be appreciated. Consequently, it is believed that, even thought the colour analysis made in this section didn't have very significant results, there is definitely a significant change in the visual and colour appearance of the fruit throughout the different ripening process, especially with bananas and avocados.

However, it is also important to highlight that the colour of the skin, more especially with mangoes, didn't give important information about the ripening stage, as at the very unripe stage we had both green and red mangoes and none of them changed their colour during the ripening process.

To end this section, below is a table listing the visual aspect of the fruits on the first, ninth and last day of measurements (on which day the fruit was opened and its internal state assessed):

Table 5. *Visual aspect of fruit during ripening*

Fruit	*Day 1*	*Day 9*	*Day 12*
Avocado 1	Very hard	Soft	Perfectly ripe but slightly rotten at the top
Avocado 2	Very hard	Soft	Half in perfect condition and half rotten
Avocado 3	Very hard	Slightly soft	Perfectly ripe but slightly rotten at the top
Avocado 4	Very hard	Very soft	Rotten
Avocado 5	Very hard	Very soft	Rotten
Avocado 6	Very hard	Hard	Rotten
Avocado 7	Very hard	Soft	Rotten
Avocado 8	Very hard	Hard	Rotten
Mango 1	Very hard	Hard	Partially rotten
Mango 2	Very hard	Slightly soft	Perfect condition

Mango 3	Very hard	Soft	Perfect condition
Mango 4	Very hard	Hard	Rotten inside
Mango 5	Very hard	Soft	Partially rotten
Mango 6	Very hard	Soft and top rotten	Rotten
Mango 7	Very hard	Soft	Really nice
Mango 8	Very hard	Soft and top rotten	Rotten
Banana 1	Very hard	Soft and quite brown	In perfect condition but really ripe
Banana 2	Very hard	Soft and quite brown	In perfect condition but really ripe
Banana 3	Very hard	Soft and quite brown	In perfect condition but really ripe
Banana 4	Very hard	Soft and quite brown	In perfect condition but really ripe
Banana 5	Very hard	Soft and quite brown	In perfect condition but really ripe
Banana 6	Very hard	Soft and quite brown	In perfect condition but really ripe
Banana 7	Very hard	Soft and quite brown	In perfect condition but really ripe
Banana 8	Very hard	Soft and quite brown	In perfect condition but really ripe

Analyzing the data of the table, it can be appreciated how the hardness of the peel cannot determine whether the fruit is ripe or not. This statement can be corroborated though the results obtained:

- Avocado nº4 on day 9 was very soft and rotten, while Avocado nº 1 was soft and in perfect condition. On the other hand, avocado nº 6 and nº8 were hard but rotten, while on the first day all avocados were hard and unripe.
- Mangos nº1 and nº4, on day 9, were hard and partially rotten, while on the first day all mangoes were hard and unripe. On the other hand though, mangos nº 2, nº3 and nº7 were soft but in perfect condition, while nº5, nº6 and nº8 were soft and rotten.
- With the bananas, we can observe that they were all in perfect condition when opened, even though they looked rotten from the outside (See figure 27).

Therefore, we can affirm that the hardness of the peel can't determine whether an avocado, banana or mango is ripe and in good condition or not.

4.4.5 Impedance and weight relationship

In the following section, the relationship between banana impedance and weight is evaluated. To do so, three days were chosen (1st, 7th and last day) and they were used to analyze how this relationship evolves during the ripening stages.

The chart here below shows this relationship for the bananas.

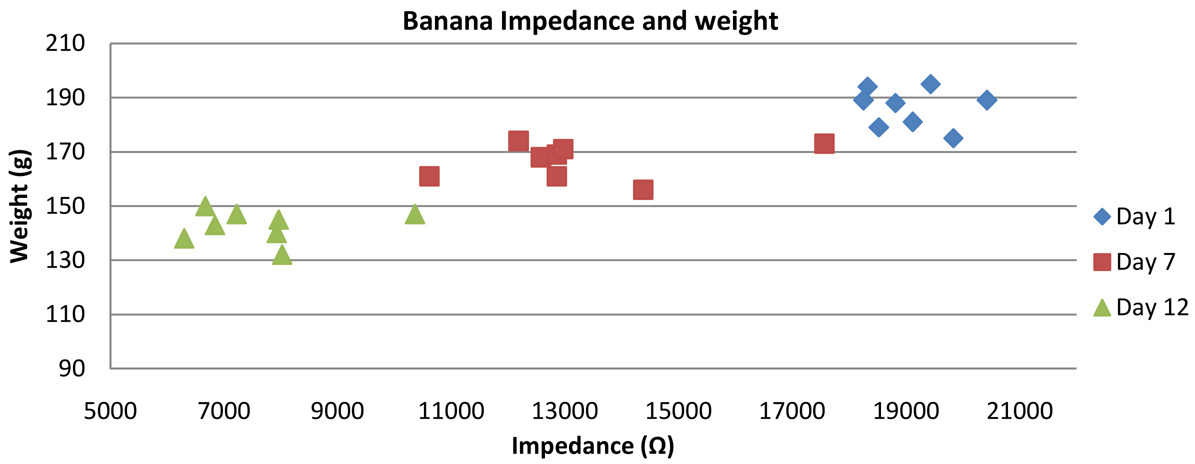


Figure 41. *Relationship between the electrical impedance and the weight evolution of mangos.*

By analyzing the chart above, we can see a clear tendency if we compare the results between the three days in an overall analysis: the higher the weight is, the higher the impedance is. However, if we focus on the results obtained each day, we can see that in this smaller scale, the relationship weight-impedance is not so conclusive. We can observe that with a similar value of weight, the impedance values obtained are slightly different. Nevertheless, we can also see that this variation is fairly low.

However, we can also observe that on the first and last day of analysis, the difference between similar values of weight and the respective impedance values obtained for the same day is not that big, whereas in the middle of the ripening process (day 7), this difference is higher, showing some outliners aswell.

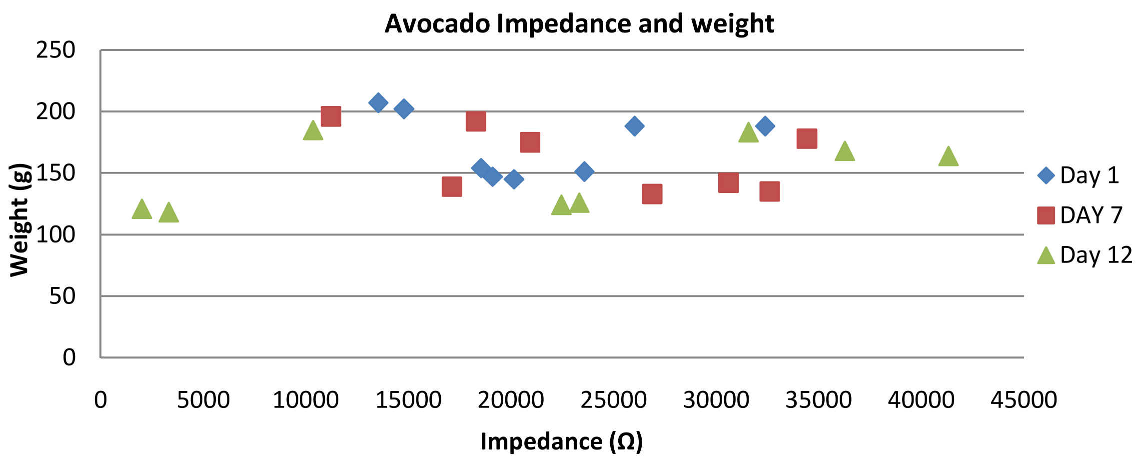


Figure 42. *Relationship between the electrical impedance and the weight evolution of avocados.*

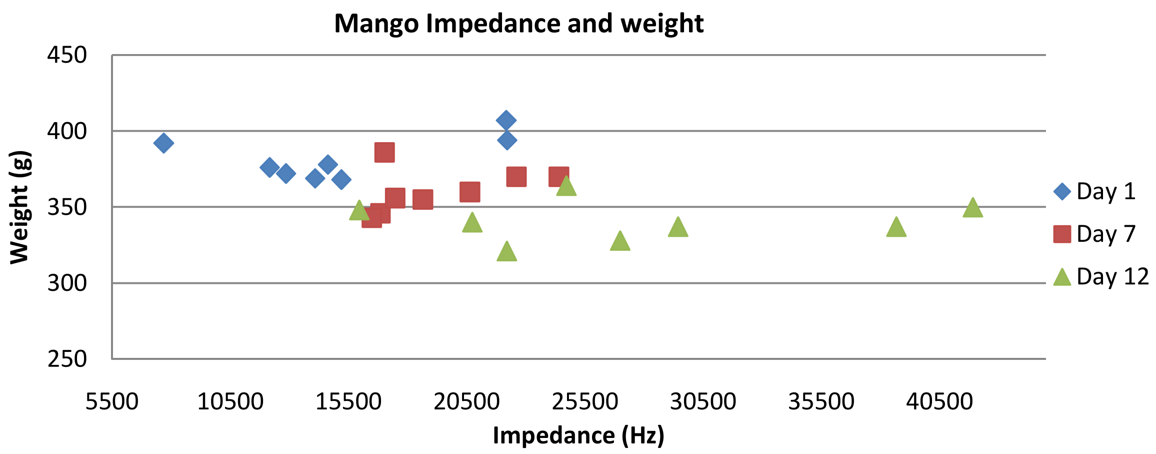


Figure 43. *Relationship between the electrical impedance and the weight evolution of mangos.*

Contrary to banana's behaviour, we can see that avocados don't show the same behaviour, neither on the overall analysis of the three days, nor on each day's smaller scale analysis.

As the avocado chart above shows, the dispersion of the points is very high, without showing any tendency between the weight of the fruit and the electrical impedance obtained.

However, mangoes weight decreases as the electrical impedance of mangoes increases

4.4.6 Sensitivity analysis

In this section, the sensitivity of the measurements is analyzed by comparing the measurements made with different positions of electrodes during three different days of analysis. Therefore, as has previously been stated, two different positions of electrodes were placed on the skin of the banana nº4, avocado nº2 and mango nº3: the first position was the same one that was used during all the experiment and the other one was completely different [See section "4.3.3.2. Sensitivity Analysis" for further information about the positions used].

Therefore, the following charts include the peak values of the impedance measurements that were made on the 2nd, 7th and 12th day with both the common position and the other one used to check the sensitivity of the fruit:

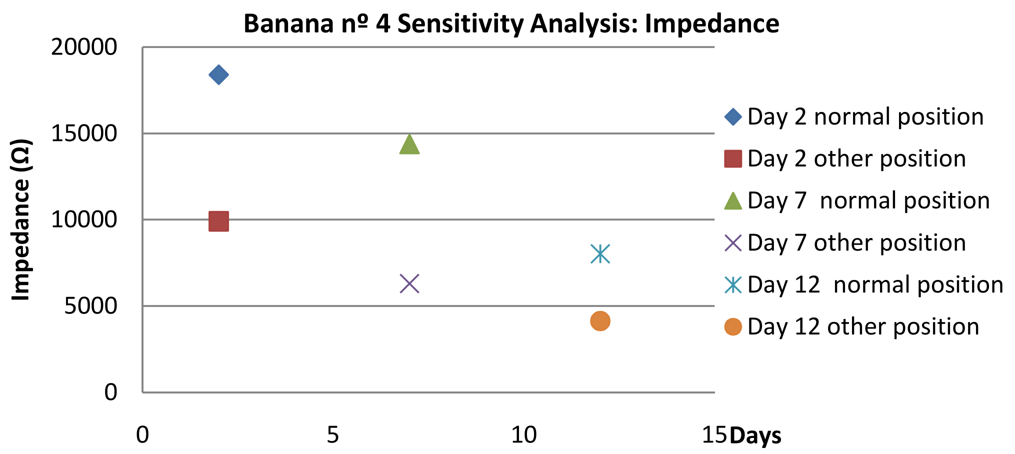


Figure 44. *Banana nº 4 sensitivity analysis: Impedance*

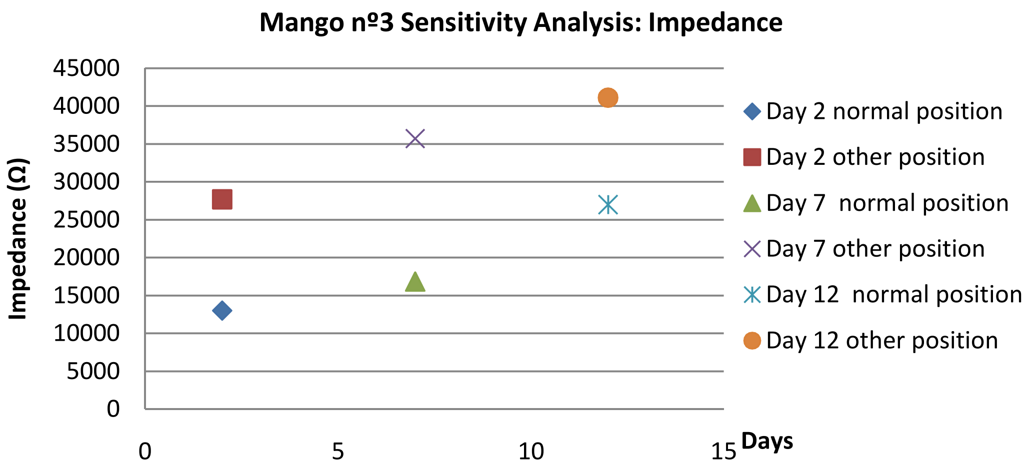


Figure 45. *Mango nº 3 sensitivity analysis: Impedance*

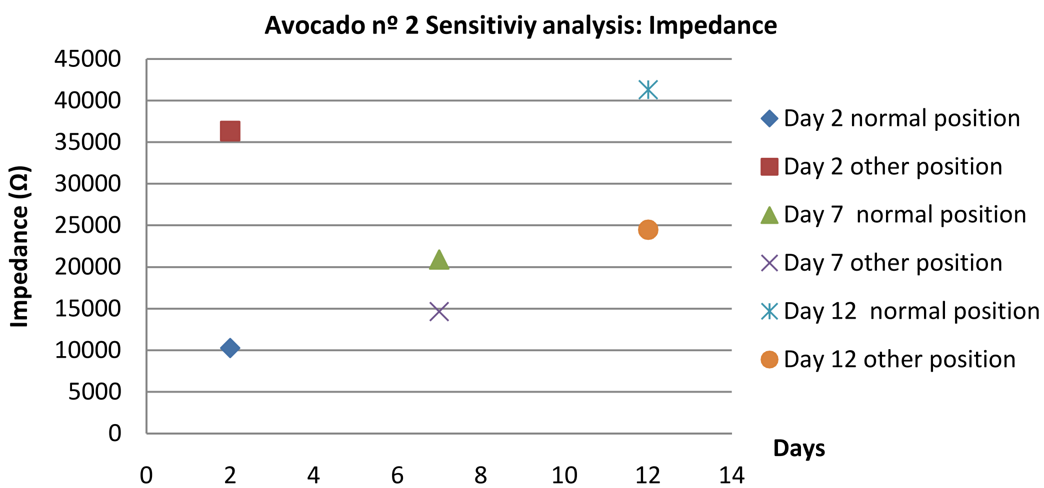


Figure 46. *Avocado nº 2 sensitivity analysis: Impedance*

Several conclusions can be reached by analysing the charts above and several behaviours can be appreciated:

- For the banana fruit, the results obtained with the different position measurements are all lower than the ones taken with the standard one.
- The mango though, shows the opposite behaviour: higher impedance results with the different position than with the standard one.
- On the other hand, the avocado shows an irregular behaviour, having a higher impedance value on day 2 with the other position, and a lower one with the standard position. However, it shows a lower value on day 7 and 12 with the different position and a higher impedance value for the standard one.

Therefore, we can conclude that the results obtained when using a different position of electrodes are quite different and it is a fact that should be taken in consideration when measuring the fruit impedance with the method used in this thesis.

However, it is important to remark that the impedance results used in the previous sections of this project are not influenced by this high sensitivity of the electrodes, as the same standard position was used for taking all the measurements.

Following the same procedure as with the impedance sensitivity analysis, the following charts include the peak values of the phase measurements that were made on the 2nd, 7th and 12th day with both the common position and the other one which was used to check the sensitivity of the fruit.

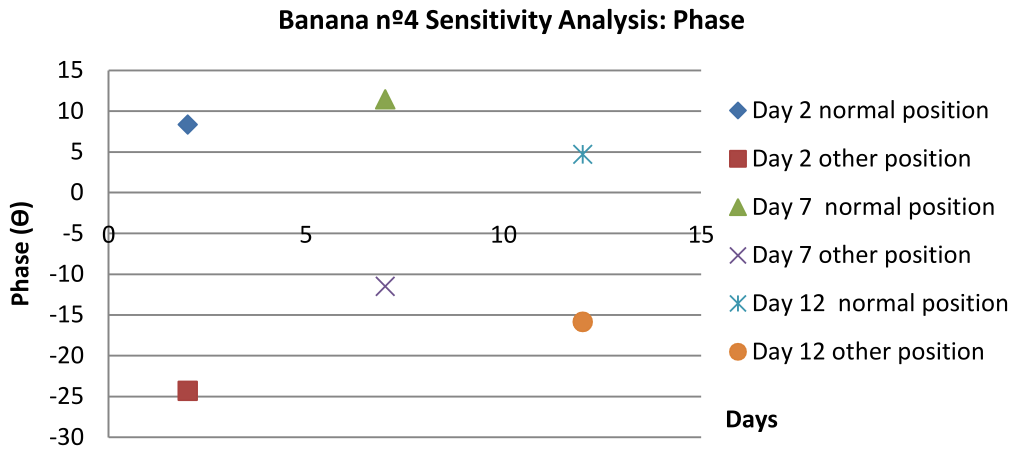


Figure 47. *Banana nº 4 sensitivity analysis: Phase*

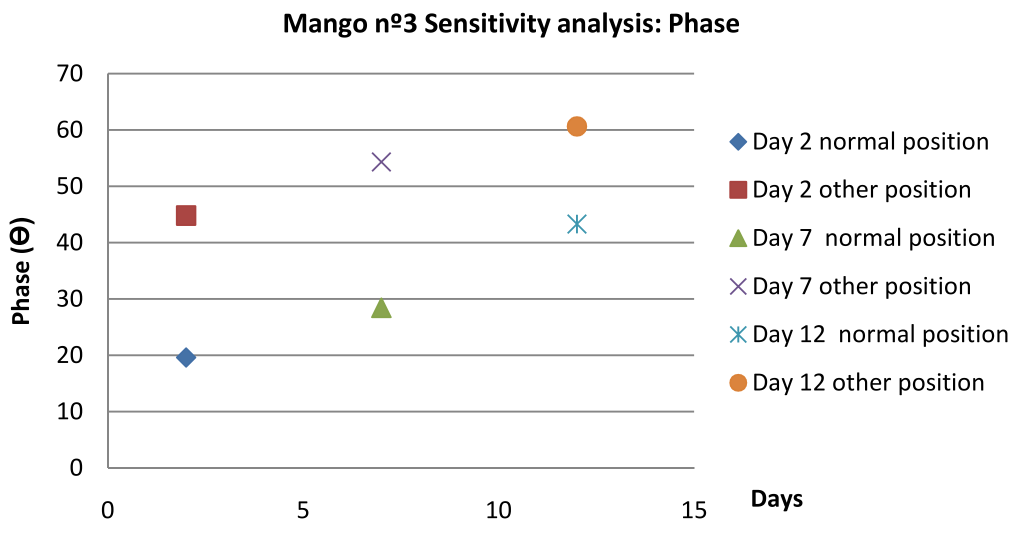


Figure 48. *Mango nº 3 sensitivity analysis: Phase*

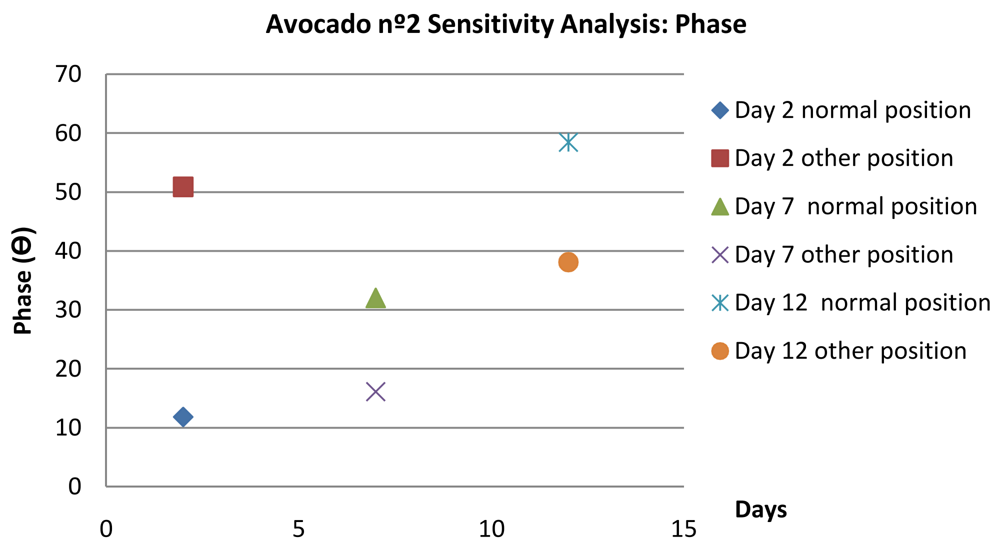


Figure 49. *Avocado nº 2 sensitivity analysis: Phase*

As the charts show, the phase behaviour with different positions of the electrodes is the same as the impedance one: we can conclude that the results obtained when using a different position of electrodes are quite different and it is a fact that should be taken in consideration when measuring the fruit phase with the method used in this thesis.

5 DISCUSSION

This chapter includes both an overall discussion about the results obtained and some hypotheses that are made to provide explanations for the results. Furthermore, the limitations that the study had to face are also exposed, as well as the inaccuracy in the results.

5.1 Discussion of the weight measurements

To begin with, in reference to the weight, the results showed that the evolution of this parameter for all three fruits follows a linear decreasing evolution, meaning that the weight loss for each piece of fruit is more or less constant and linear, following similar mathematical slopes. It is interesting to note that the accuracy of the scale was very high, having a tolerance of only +/- 0,5 grams.

Therefore, the results obtained in reference to weight were quite accurate.

Moreover, in reference with the day-to-day weight loss, the results found showed that bananas and mangoes don't loss the same weight, while the day-to-day weight loss of avocadoes is fairly constant, independently of the original weight.

5.2 Discussion of the impedance and phase evolution

In reference to the impedance evolution, different results were obtained:

To begin with, the results show that the bananas exhibited lower values of impedance as they ripen. Furthermore, the mangoes showed an increasing tendency of impedance throughout the ripening days, but the standard deviation of these results was higher than the one obtained with the bananas.

However, it was not possible to determine the tendency of the avocado impedance during ripening, as the data obtained was too disperse and the tendency too irregular.

Consequently, a hypothetical explanation of the result of the avocados' electrical spectrometry could be that the electrodes didn't function properly on this fruit's skin. As previously stated, the electrodes had to be attached to the fruit's skin. However, this task was not totally successful with the avocados, as their skin is quite rough and irregular, and the electrodes weren't fully stuck to the fruits, making it a hypothetical explanation for the results obtained.

On the other hand, we could also appreciate that there was no noticeable relationship between the phase and the ripening process for none of the fruits, making it an insignificant parameter to determine fruit ripeness.

In conclusion, all this analysis show that different fruits exhibit different impedance behaviour during fruit ripening.

5.3 Discussion of the colour analysis

The colour analysis made in this project with the Fiji software didn't have very significant results. Nevertheless, it was obvious that there was definitely a significant change on the visual and colour appearance of the fruit throughout the different ripening process, and we speculate that this change could be possibly obtained with a different analysis technique.

Therefore, it is believed that the results obtained with the pictures that were took and the analysis of the Fiji software weren't accurate enough, as they couldn't properly show the fruit's colour evolution.

In addition to this, it is also important to highlight that the colour of the skin, more especially with mangoes, didn't give important information about the ripening stage, as at the very unripe stage we had both green and red mangoes and none of them changed their colour during the ripening process.

Finally, the visual aspect of the fruits on the first, ninth and last day of measurements (on which day the fruit was opened and its internal state assessed) showed that the hardness of the peel can't determine whether an avocado, banana or mango is ripe and in good condition or not, as with the same hardness state, the different fruits showed different conditions.

5.4 Discussion of the weight and impedance relationship

Diversely, the impedance and weight relationship analysis showed that, on a small scale (in the same day), the impedance measured is independent of weight, but the variation of the values is fairly low.

However, in an overall analysis, the results showed how as the weight increases, the electrical impedance of bananas also increase. In contrast to this, it also showed that the mangoes weight decreases as the electrical impedance of mangoes increases.

Nevertheless, this relationship for the avocados didn't show any tendency between the weight of the fruit and the electrical impedance obtained.

5.5 Discussion of the sensitivity analysis

With the sensitivity analysis it was proven that the electrodes showed high sensitivity when changing position, as different impedance and phase results were obtained when taking measurements with different positions.

Under certain assumptions, this might possibly be due to the geometry of the fruit and the way that the electrical current circulates inside the fruit depending on the position of the electrodes.

Therefore, it is advised to take into consideration this high sensitivity of the electrodes for further usage of the results of this project, by using preferably the same position as was used in this project.

5.6 Limitations of the study

The most important limitation that the study had to face was the range of frequencies that the board could work with- the swipe of frequencies could only be made for the range of frequencies of 1000Ω to 100.000Ω. Therefore, lower frequencies, which may also have been of interest, could not be analyzed.

Moreover, it is important to stress that, although the measurements were taken at the same time every day and the room where the fruit was stored kept (as near as possible) at a constant 20ºC, these were not laboratory conditions by any means. Therefore, although the AD5933 board exhibits high accuracy, it would have been advantageous to be able to compare the result we obtained with values measured using laboratory equipment.

6 CONCLUSIONS

So as to achieve the goals of this project that are stated at the introduction of the thesis, several procedures were done.

On the first place, the study of the ripening process and the different measurable parameters that can determine fruit quality were studied through literature research. After understanding the ripening process and thanks to literature review, the techniques that I was aiming to use to develop the experiment were chosen, as well as both all the parameters that were about to be measured and the tools that were needed to do such task. As soon as the tools were received, the experimental set up to measure the parameters was built successfully and both the calibration procedure and the pre-experimental try-outs were made.

When these tasks were fulfilled, the experiment started and went through during 12 days.

Finally, all the measured data was processed and analyzed through statistical analysis, which helped to interpret the results and notice whether there was any relationship between the parameters.

In conclusion and as an overall analysis of the procedures exposed above, I consider that the goals of the project were reached.

6.1 Recommendations for further research

Furthermore, I would like to highlight how that, accordingly to the behaviours that are found in the experimental results and in the discussion of results sections, some recommendations for further research and innovation would be:

- To use and try the performance of different kinds of electrodes, especially for avocados, and to check if their performance is more accurate than the one obtained in this project.
- To compare the results obtained with the AD5933 board to results obtained with laboratory equipment.
- To do further research about the positions of the electrodes and study how this aspect could be controlled in a supermarket environment with intended users.
- To use another colour spectrometry method to determine the change of the visual aspect and the colour variation of the fruit. Even though some of the fruits didn't show any kind of relationship between the colour and the ripening state, it is believed that the colour evaluation would also be a matter of interest for further research and therefore, different techniques to the ones exposed in this project should be used.

To conclude, the data and results obtained in this project regarding fruit ripeness with the electrical impedance spectrometry are believed to be a very useful tool for further studies to improve this conceptual device, build a physical prototype and therefore, contribute to food quality research as well as to go a step closer to reduce food waste.

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APPENDIXES

In this section, all the results obtained during the experiment are attached. Therefore, the measurements of impedance, phase, weight and colour are found in the following tables.

A. Weight measurements

Table 6. *Weight measurements in grams (g)*

FRUIT	DAY 1	DAY 3	DAY 5	DAY 7	DAY 9	DAY 11	DAY 12
Avocado 1	202	198	195	192	189	185	183
Avocado 2	188	184	179	175	171	167	164
Avocado 3	207	204	199	196	191	187	185
Avocado 4	188	185	182	178	174	170	168
Avocado 5	151	147	143	139	134	130	126
Avocado 6	154	150	147	142	137	132	121
Avocado 7	147	143	139	135	130	127	124
Avocado 8	145	141	137	133	130	123	118
Mango 1	407	400	393	386	377	369	364
Mango 2	394	385	379	370	362	354	350
Mango 3	368	360	354	346	339	332	328
Mango 4	378	370	364	356	349	341	337
Mango 5	392	385	379	370	362	353	348
Mango 6	372	366	362	355	348	341	337
Mango 7	369	358	352	343	335	326	321
Mango 8	376	370	366	360	352	344	340
Banana 1	195	189	182	173	163	153	145
Banana 2	181	173	168	161	152	144	138
Banana 3	194	186	183	174	165	156	150
Banana 4	175	168	163	156	148	139	132
Banana 5	188	181	176	168	159	150	143
Banana 6	179	174	167	161	153	145	140
Banana 7	189	181	176	169	161	153	147
Banana 8	189	184	179	171	162	153	147

B. Colour measurements

Table 7. *Colour evolution in %*

FRUIT	COLOUR	DAY 1	DAY 3	DAY 5	DAY 7	DAY 9	DAY 11	DAY 12
MANGO	RED	51,8%	52,8%	54,51%	53,8%	56,0%	57,2%	55,8%
MANGO	GREEN	29,8%	28,7%	28,77%	29,9%	28,7%	28,3%	28,3%
MANGO	BLUE	18,4%	18,5%	16,72%	16,2%	15,3%	14,9%	15,9%
BANANA	RED	44,0%	48,0%	51,5%	49,0%	52,5%	48,1%	44,7%
BANANA	GREEN	45,1%	40,4%	39,4%	37,9%	36,0%	33,3%	32,8%
BANANA	BLUE	10,9%	11,6%	9,1%	13,1%	11,4%	18,5%	22,6%
AVOCADO	RED	37,9%	39,4%	41,7%	36,8%	39,3%	37,7%	37,3%
AVOCADO	GREEN	43,8%	38,8%	31,9%	32,0%	31,4%	31,5%	31,4%
AVOCADO	BLUE	18,3%	21,8%	26,4%	31,2%	29,3%	30,8%	31,3%

C. Impedance and phase measurements

The data of the impedance and phase measurements is found in all of the charts that have been created for the analysis of the results, which can be found in section “4.4. Experimental Results”. Moreover, the excel sheets attached to the thesis contain all of the impedance and phase results that were obtained. Furthermore, below, the first page of the AD5933 board data sheet is included.

ANALOG DEVICES

1 MSPS, 12-Bit Impedance Converter, Network Analyzer

AD5933

FEATURES

- Programmable output peak-to-peak excitation voltage to a max frequency of 100 kHz
- Programmable frequency sweep capability with serial I²C® interface
- Frequency resolution of 27 bits (<0.1 Hz)
- Impedance measurement range from 100 Ω to 10 MΩ
- Internal temperature sensor (±2°C)
- Internal system clock option
- Phase measurement capability
- System accuracy of 0.5%
- 2.7 V to 5.5 V power supply operation
- Temperature range −40°C to +125°C
- 16-lead SSOP package

APPLICATIONS

- Electrochemical analysis
- Bioelectrical impedance analysis
- Impedance spectroscopy
- Complex impedance measurement
- Corrosion monitoring and protection equipment
- Biomedical and automotive sensors
- Proximity sensing
- Nondestructive testing
- Material property analysis
- Fuel/battery cell condition monitoring

GENERAL DESCRIPTION

The AD5933 is a high precision impedance converter system solution which combines an on-board frequency generator with a 12-bit, 1 MSPS, analog-to-digital converter (ADC). The frequency generator allows an external complex impedance to be excited with a known frequency. The response signal from the impedance is sampled by the on-board ADC and a discrete Fourier transform (DFT) is processed by an on-board DSP engine. The DFT algorithm returns a real (R) and imaginary (I) data-word at each output frequency.

The magnitude of the impedance and relative phase of the impedance at each frequency point along the sweep is easily calculated using the following two equations:

$$Magnitude = \sqrt{R^2 + I^2}$$

$$Phase = Tan^{-1}(I/R)$$

Table 1. Related Devices

Part No.	Description
AD5934	2.7 V to 5.5 V, 250 kSPS, 12-bit impedance, 16-lead SSOP

FUNCTIONAL BLOCK DIAGRAM

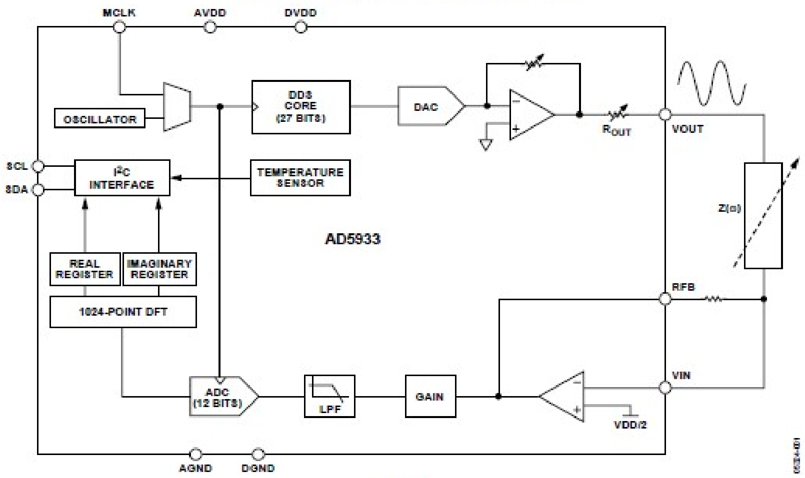

Figure 1.

Rev. 0

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