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Non-destructive testing of the relationship between apple storage technologies and physical parameters

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Salma Kassebi

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Denomination: Doctoral School of Mechanical Engineering

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Leader: Prof. Dr. Gábor Kalácska, DSc.
Institute of Technology
Hungarian University of Agriculture and Life Sciences,
Szent István Campus, Gödöllő, Hungary

Supervisor: Dr. habil. Péter Korzenszky, PhD.
Institute of Technology
Hungarian University of Agriculture and Life Sciences,
Szent István Campus, Gödöllő, Hungary

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Affirmation of supervisor Affirmation of head of school

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NOMENCLATURE AND ABBREVIATIONS

Symbols

a*	Green/red coordinate in the CIELab colour space (-)
b*	Blue/yellow coordinate in the CIELab colour space (-)
C*	Chroma (-)
d	Diameter (mm)
ΔE	Colour Difference (-)
Δm	Weight loss percentage (%)
Δm_a	Absolute weight loss (g)
F (F-statistic)	A ratio (-)
h^o	Hue angle (^{o})
L*	Lightness, black/wite coordinate in the CIELab colour space (-)
m	Mass (g)
p (p-value)	Probability value (-)
R^2	Coefficient of determination (-)
RH	Relative Humidity (%)
T	Temperature (°C)
TSS	Total soluble solids (%)
w	weeks (-)

Abbreviations:

1-MCP	1-methylcyclopropene
ANOVA	Analysis of Variance
ATP	Adenosine Triphosphate
CA	Controlled atmosphere
CIELab	International Commission on Illumination (CIE)
CMYK	Cyan, Magenta, Yellow, Key (Black)
D03	Darkroom storage at 3°C
D15	Darkroom storage at 15°C
D24	Darkroom (ambient) storage at 24°C
EMM	Estimated Marginal Means
HACCP	Hazard Analysis and Critical Control Points

HPLC	High-performance liquid chromatography
HSV	Hue Saturation Value
LED	Light-emitting diode
L03	Lightroom storage at 3℃
MAP	Modified Atmosphere Packaging
MA	Modified atmosphere
NTC	Negative Temperature Coefficient
PPO	Polyphenol oxidase
PVC	Polyvinyl Chloride
Q10	Temperature coefficient
RGB	Red Green Blue
SSC	Soluble solid content
TA	Titratable acidity
USB	Universal Serial Bus
UV	Ultraviolet light
XYZ	Colour space based on the CIE

1. INTRODUCTION, OBJECTIVES

This chapter is about presenting the background and purpose of the present research.

1.1. Introduction

Over the years, fruits have been appreciated as an essential component of the human diet because of their excellent sensory qualities and positive impact on human health. Fruit quality, appearance, and mechanical qualities under various conditions, especially temperature and shelf life, have been the main focus of post-harvest fruit preservation research. (Payne et al., 2012). Fruits are rich in essential vitamins, minerals, fibre, and antioxidants; these components positively impact human health. They contribute to preventing chronic diseases, including cardiovascular conditions, obesity, diabetes, certain types of cancer, and inflammation. Their remarkable nutritional profile and strong ecological adaptability have favoured them highly by producers and consumers (Paredes-López et al., 2010). Fruits serve as a rich source of water, carbohydrates, soluble solids, organic acids, and dietary fibre.

For years, research into the post-harvest preservation of fruit has focused on storage parameters, such as temperature and storage duration, directly affecting stored fruits' quality, appearance, and mechanical characteristics (Ziv & Fallik, 2021).

In the past, fruit was usually consumed fresh at the place of production. However, technological advances in post-harvest and storage have made transporting fruit to different regions possible. As a result, they are consumed a few days, or even several days, after their harvest date.

Maintaining fruit quality along the supply chain is challenging, especially regarding storage and transportation (Teshome et al., 2023). According to a study by Xue et al. (2021), half of the fruit (45-55%) is lost during handling and storage after harvest. On the other hand, meat, fish, and cereals have lower loss levels at 30%, 35%, and 20%, respectively.

Weight loss Percentage and moisture loss are the other terms used to characterise water loss (Paniagua et al., 2013). Water loss, even at modest levels of 3-10%, negatively impacts fruit (Maw & Mullinix, 2005), which alters its flavour and taste, destroys its nutrients, and makes it more susceptible to bacterial contamination (Hossain et al., 2020). One of the most challenging issues facing the globe today is how to store fruit after harvest. Storing fruit at low temperatures immediately after harvest reduces its respiration rate. As a result, shelf life increases while preserving nutritional and sensory qualities and reducing post-harvest losses (Rahmadhanni et al., 2020). According to Falah et al. (2015), fruit stored at high temperatures has a shorter shelf life and suffers quality degradation. Moisture loss in the commercial world is also a financial concern

as it diminishes visual appeal and causes a decrease in turgor pressure, which results in softening (Gidado et al., 2024).

This research will lead to a better understanding and optimisation of the storage process, which will help extend fruit shelf life. It will provide an overview analysis of changes in parameters, namely weight loss percentage and colour, during storage at different temperatures of Golden Delicious apples.

The new findings will be helpful in the post-harvest technology sector, which is looking for solutions to the storage challenges of perishable fruit. Our results will give an overview of the correlation between weight loss percentage and other parameters, and this cross-over research area will not just help minimise the deterioration of quality but also preserve the characteristics of fruit desirable to consumers.

1.2. Objectives

The global apple market requires stringent quality control measures, particularly for commercially important cultivars like Golden Delicious, one of the most important and best-known apple varieties in the world today. For traders, weight loss percentage represents a direct economic impact since apples are sold by weight, and even modest reductions in mass can significantly affect profitability. Postharvest analysis showed that approximately 85-90% of weight loss occurs through transpiration-driven water loss, while the remaining portion stems from metabolic respiration processes.

Apple colour change is one of the primary criteria for consumers when purchasing apples. This study investigates the changes in physical parameters of apples over 12 weeks under various storage conditions, with the goal of developing practical monitoring approaches. The dissertation includes pH measurements and total soluble solids at the beginning and end of storage to support the development of non-destructive monitoring systems and enable more informed storage and inventory decisions.

This study investigates the storage of Golden Delicious apples under four different conditions: dark room storage at three different temperatures and light room storage, each at a constant relative humidity, for 12 weeks.

The study will help optimise storage practices and maintain fruit quality in line with the expectations of retailers and consumers. The experiments and measurements consider the most critical aspects of storage: relative humidity and temperature.

The overall objective of the study is to investigate the weight loss percentage and colour parameters of Golden Delicious apples over a 12-week period, considering different storage conditions.

The detailed research objectives can be described as follows:

1. To assess how different storage temperatures affect the weight loss percentage of Golden Delicious apples during storage.
2. To assess how different storage temperatures affect the colour change of Golden Delicious apples during storage.
3. To assess how different storage temperatures affect the hue angle of Golden Delicious apples during storage.
4. To assess how the same storage temperatures affect the weight loss percentage of Golden Delicious apples, changes in the dark chamber and the light chamber.
5. To assess how the same storage temperatures affect the hue angle of Golden Delicious apples, changes in the dark chamber and the light chamber.
6. To establish whether the measurement data generated by the performed experimental series show a significant difference based on statistical analysis.

2. LITERATURE REVIEW

This chapter examines fruit quality components, such as colour and weight. It delves into various quality assessment methods, both sensory and instrumental, and analyses essential principles of fruit storage, focusing on critical parameters like humidity and temperature. Additionally, the chapter examines various technologies for assessing and controlling fruit parameters, including non-destructive testing techniques. Additionally, it examines post-harvest storage conditions for fruits.

2.1. Components of fruit quality

2.1.1. Definition of quality

Quality encompasses a high degree of excellence and a high standard of merit. According to Pattee (1985), food quality is the collection of traits that distinguish individual product units and are critical in determining their acceptability to customers. The consistency of a food product is a multifaceted and complex property that includes measured and objective quality and sensory characteristics (Schnitzler & Gruda, 2002). Quality issues have gotten much coverage over the last few decades.

2.1.2. Attributes of fruit quality

Fruits are distinguished by their four primary characteristics: colour and appearance, flavour (taste and perfume), texture, and nutritional content. A product's external appearance is one of its most crucial qualitative attributes, as it also influences its acceptance or rejection (Barrett et al., 2010). Dietary consistency has an underlying impact on the human body. Consumers, researchers, and the medical community increasingly know this consistent feature. Consumers are attracted to a fruit or vegetable by its form, size, gloss, and vibrant colour.

Coolness, sweetness, and other flavour characteristics are essential to the enjoyment of eating. The flavour is associated with the fragrances of a fruit, while it also encompasses both aroma and taste. When consuming a fruit, these sensory attributes are perceived simultaneously; we may taste the sweetness, thickness, hardness, toughness, or crunchiness. The texture of the products varies as chewing progresses, and in most situations, the products become softer. The nutrient content is a highly desirable product quality that cannot be seen, tasted, or smelled. Nutrients are essential for the body's development and long-term well-being and have both micro and macro components (Pattee, 1985).

Fruit colour is mainly determined by water-soluble pigments like anthocyanins (red, blue), flavonoids (yellow), and betalains (red), as well as lipid-soluble pigments like chlorophylls (green)

and carotenoids (yellow, orange, and red). Additionally, enzymatic and non-enzymatic browning reactions form water-soluble pigments in shades of orange, grey, and black. A food item's brightness is determined by its ability to reflect light, with freshly harvested produce generally exhibiting higher brightness levels.

The flavour is a complex and cohesive experience that encompasses senses of taste, fragrance, pressure, and skin sensations, such as mild touch, colour, or light discomfort (Vilela, 2021). The word flavour describes both scent (smell) and flavour (taste). Taste is detected through the mouth by chewing food, while aroma is a volatile substance mainly perceived through the nose.

Total Soluble Solids (TSS) are water-soluble substances that comprise sugars and organic and inorganic molecules. They are a key indicator of fruit quality and influence its sweetness and overall flavour profile. TSS determination has traditionally been based on destructive methods. The most common method is to use a refractometer and apply a drop of fruit extract to the instrument's prism. The measurement is reported in degrees Brix (González-Caballero et al., 2010).

Fruits have varying pH levels, which determine their acidity or alkalinity. Most fruits are known for their slightly acidic properties (Merga & Bekele, 2024).

The pH properties of fruits can affect their taste, texture, and nutritional value (Andrés-Bello et al., 2013). Additionally, the pH level of fruits can impact their preservation and processing, as acidic fruits are more resistant to spoilage due to their ability to create an unfavourable environment for spoilage-causing microorganisms (Alegbeleye et al., 2022).

Storage conditions and duration affect the pH value of certain fruits. For example, the pH value of the Hass avocado on days 24 and 32 (pH of 7.0) showed a slight increase compared to the first day (pH of 6.7) (Vázquez-López et al., 2022). The fruit development stage and variety also play a role in determining pH. According to Kookal & Thimmaiah, (2018) the pH of banana fruit increased with ripeness. Suwanti et al. (2018) reported that during storage, the pH of all papayas increased, attributed to the conversion of carbohydrates to sugar and the use of acids for metabolism.

2.1.3. Methods of quality measurements

Fruit consistency can be assessed using both sensory and instrumental approaches. Sensory evaluation methods are more effective for developing new products and determining product standards, whereas instrumental techniques are more appropriate for systematic and repetitive consistency assessments (S. S. Q. Rodrigues et al., 2024).

2.1.3.1. Sensory methods of quality measurement

There are extensive examples of sensory methods for assessing food quality in general, as well as fruit and vegetable processing quality in particular (S. S. Q. Rodrigues et al., 2024). Affective and

methodological measures are used in food sensory studies. Analytical experiments are used to either detect potential discrepancies (difference tests) or to provide an overview of the substance (description tests) (descriptive analysis). Small panels with any level of panellist experience usually perform sensory analytical measures. Affective tests determine preference (which samples are favoured over others) and often include many naive panellists. Using sensory approaches to define content has many benefits. It is possible to explain quality characteristics in acceptable ways to consumers by including human experience in sensory processing. Emotional checks for customers are the most effective way to learn about their preferences and dislikes. Sensory descriptive panels may detect slight differences in consistency between similar samples (Sipos et al., 2021).

2.1.3.2. Instrumental methods of quality measurement

The instrumental techniques used for measurements cover a range of methods for determining colour, appearance, flavour, texture, and nutritional content (Kader, 2002). Table 2.1 shows an updated edition of the quality assessment methods.

Table 2.1. Instrumental methods for the determination of fruit quality

Attribute	**Common Instrumental Techniques**	**Examples of Instruments/ Methods**	**Key Parameters Measured**	**References**
Colour and Appearance	-Hyperspectral Imaging -Digital Imaging Analysis - Computer Vision	-Hyperspectral Imaging Systems, -Multispectral Cameras	-External Colour Indices (L*,a*,b*) -Surface Defects -Ripeness Indicators	(C. Zhang et al., 2024) (Santos Pereira et al., 2018 (Hadimani & Mittal, 2019)
Flavour (Aroma and Taste)	-Gas Chromatography-Mass Spectrometry (GC-MS) -Electronic Noses (E-noses)	-GC-MS for Volatile Profiling, -E-nose Sensor Arrays	-Aroma Compounds, -Volatile Profiles, -Flavour Markers	(Bi et al., 2020) (Baietto & Wilson, 2015)
Texture	-Texture Profile Analysis (TPA) - Rheometry - Compression and Penetration Tests	-Texture Analysers, -Penetrometers -Rheometers	-Firmness, -Hardness, -Elasticity, -Cohesiveness	(Singh et al., 2013) (Caparino et al., 2017) (Dantas et al., 2017)
Nutritional Content	-Near-Infrared (NIR) Spectroscopy -High Performance Liquid Chromatography (HPLC)	-NIR Spectrometers, -HPLC Systems	-Sugars, -Acidity, -Vitamins, -Bioactive Compounds	(Hernández-Hierro et al. 2022) (D. P. Rodrigues et al. 2021)

One benefit of instrumental approaches is the ability to obtain precise outcomes. A growing subset of these instrumental methods is non-destructive, allowing quality measurements without damaging or altering the sample. These methods have become increasingly relevant in postharvest and quality control research. Techniques such as impact analysis (Felföldi et al., 2017), impedance spectroscopy (Vozáry & Benkó, 2010), and multi- and hyperspectral imaging (Firtha, 2009)enable the rapid and repeatable evaluation of internal and external product attributes. These techniques have been used on a variety of horticultural crops, such as sweet peppers and pears (Zsom et al., 2014), where they provide notable benefits in terms of speed, repeatability, and the capacity to track quality over time without causing damage to the product.

Instrumental test findings are closely related to chemical and physical characteristics, which allow researchers to understand the observed variations mechanistically. The instruments are also more sensitive to minor sample differences and can spot consistency failure patterns before humans can (Brosnan & Sun, 2004). The fact that specific instrumental measurements have no relation to market acceptability is a significant drawback to instrumental evaluations, and they cannot be used to determine the quality of a given material. Both sensory and instrumental assays perform well when used in tandem, with the most appropriate measure being used to achieve the desired result (Ibañez et al., 2022).

- Colour measurement

In 1931, the International Commission on Illumination adopted the trichromatic colour measurement system based on additive colour mixing to clearly and objectively describe and define colours. This system was supplemented with a new modification in 1962. Since then, this colour definition system has been accepted everywhere, and its application is gaining popularity.
The CIE colour system assigns a colour triad to each colour. Observations show that colour is a three-dimensional quantity, which is undoubtedly because our eyes perceive colours with three receptors: the protos, which are sensitive to red; the deuterons, which are sensitive to green; and the trios, which are sensitive to blue.
Three measurement principles are known for measuring colours (György et al., 2015): comparison with colour samples, spectral measurement, and tristimulus measurement.
We use colour measurement instruments to measure colours. According to the applied measurement principle, these can also be of three types: visual colour-measuring instruments, spectrophotometric colour-measuring instruments and tristimulus colour-measuring instruments.
Colour-measuring instruments are also usually distinguished based on the quantity to be measured:

- Measuring the colour of coloured surfaces (reflective colour measuring instruments)

- Measuring the colour of coloured, transparent media (coloured liquids, colour filters, coloured glasses) (Transmission colour measuring instruments)
- Measuring the colour of coloured lights (spectroradiometers)

The most common task is measuring the colour of coloured surfaces with a colour-measuring instrument operating on the reflection principle.

Colour may be determined using non-destructive methods such as visual or physical inspection. Such methods typically focus on calculating light absorbed from or emitted by a product's surface. Colour perception requires three components: 1) a light source, 2) an entity that modifies the light through reflection or transmission, and 3) an observer's eye/brain combination (El-Mesery et al., 2019). In specific ways, sensory computational methods of analysing colour are faster and simpler than instrumental methods. They cannot require special equipment but can be standardised using colour maps or disks.

One of the drawbacks is that such approaches are subject to significant variance due to human visual discrepancies and human error. Precision may also be harmed by insufficient or poor-quality usable illumination. The instrument techniques could be more flexible and can only be used to evaluate minor differences. As shown in Fig. 2.1, some instruments are compact, while others can be accommodated on the packing side. Instrumental approaches have the following drawbacks: specific colour measurement instruments are more expensive and slower than sensory ones (Mitcham et al., 1996).

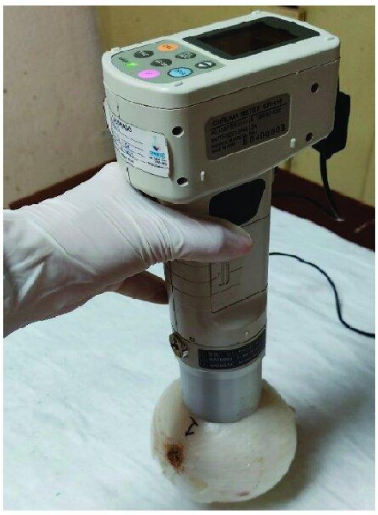


Fig. 2.1. Measuring the external colour of an onion using a Minolta colourimeter (Barrales-Heredia et al., 2023)

Various colour coordinate systems, commonly called colour spaces, are utilised to characterise the colour of an object. Figure 2.2 shows RGB, HSV, and CIELab colour space representations. The initial phase is to select the right colour space. RGB (Red, Green, Blue) is the television display's

most widely used kind. Seldom is the colourimeter's raw RGB data utilised in the food categorisation literature. Alternative RGB colour model representations, such as HSV(Pierre et al., 2015) and Lab (Hanbury, 2008), are intended to align with how the human eye interprets colour-making characteristics.

The CIELab colour space is the most commonly used due to its uniform colour distribution and close alignment with human visual perception. In this colour model, three values define colour representation: L* denotes lightness, while a* and b* correspond to the green-red and blue-yellow colour components, respectively. Humans use the chromaticity and brightness of an item to determine its colour. Two more components may be separated from the chromaticity: Saturation and hue (Syahrir et al., 2009). While saturation relates to how colourful a stimulus is in terms of brightness (Sural et al., 2002), hue is described as the degree of resemblance to particular colouration (typically red, green, blue, and yellow). (Hartmann et al., 2011). This characteristic has to do with how absorbance varies at different wavelengths. In colour analysis, a higher hue angle characterises colour differences to a neutral light grey reference and denotes a decrease in yellow intensity. The angles that represent red in this system are 0° and 360°, whereas the angles that indicate yellow, green, and blue are 90°, 180°, and 270°, respectively. The hue angle has been extensively applied in evaluating colour attributes in fruits, meats, and green vegetables (LÓPEZ et al., 1997).

Chroma (C*) measures the degree of deviation between a hue and a grey shade of the same luminance and is considered a quantitative measure of colour intensity. Higher chroma values correspond to greater perceived colour intensity in samples. The modulus of the distance vector between the initial colour values and the actual colour coordinates can be used to quantify colour changes. We refer to this idea as the total colour difference (Martins & Silva, 2002). The total colour difference, as defined by Patras et al.(2011), is the degree of variation between the colour of the stored samples and the matching control samples. This colour departure from a reference standard is determined by measuring the overall colour difference (ΔE). The HSV is a cylindrical representation where the hue is represented by the angle, starting at 0°C for red, the height is the value, and the distance to the cylinder axis represents the saturation, as shown in Fig. 2.2.

Instruments like spectrophotometers and colourimeters are frequently used to measure colour. According to Lazaro et al.(2019), colourimeters provide tristimulus values (L, a, and b) that closely resemble human eye-brain perception. Due to their durability and reliability, colourimeters are frequently employed in standard quality control assessments. In contrast, spectrophotometers are predominantly used in research and development laboratories, as they enable a wavelength-by-

wavelength spectral analysis of a material's reflectance and transmission properties, offering a more detailed interpretation of colour characteristics.

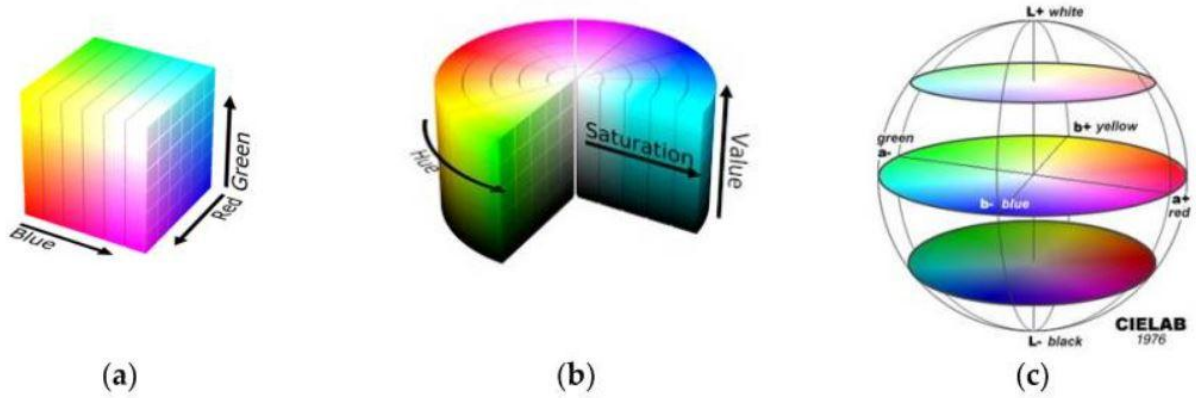


Fig. 2.2. (a) RGB colour space, (b) HSV colour space, (c) CIELab colour space (Lazaro et al., 2019)

- Appearance

Most appearance factors may be calculated using basic instruments like those shown in Table 2.2. Dimensions, weight, and volume can all be used to measure height, and there is generally a strong correlation between the two (Kader, 2002). Form is defined as the ratio between different proportions, such as the length-to-width dimensions used to characterise the shape of a carrot. In certain cases, particularly when assessing defects, quantifying their extent or severity can be challenging. In this case, taking photos or using models or sketches to create a quantitative scoring scheme is beneficial. Kader (2002) established a five-grade scoring system for evaluating various defects in fruits and vegetables (1 = no symptoms, 2 = minor, 3 = mild, 4 = major, 5 = extreme), which detailed explanations and photographs can supplement.

Table 2.2. Example of consumer sensory evaluation scales for hedonic, purchase intent, and acceptability (Barrett et al., 2010)

Hedonic	Purchase	Acceptability
9 - Like extremely	5 - Definitely would	3 - Tastes great
8 - Like very much	4 - Probably would	2 - Acceptable
7 - Like moderately	3 - Might or might not	1 - Unacceptable
6 - Like slightly	2 - Probably would not	
5 - Neither like or dislike	1 - Definitely would not	
4 - Dislike slightly		
3 - Dislike moderately		
2 - Dislike very much		
1 - Dislike extremely		

- pH and total soluble solids content

Sweet, salty, spicy, bitter, and umami are the five dimensions of flavour. Instruments can, however, be used to quantify certain flavour components. Individual sugars can be determined using HPLC, a refractometer, or a hydrometer that analyses total soluble solids, which can quantify sweetness more quickly but with less precision (Pattee, 1985). The chloride and/or sodium concentration can be measured to get a rough estimate of salinity. The pH, or more generally, absolute acidity, may be used to determine how sour anything is. Total acidity is measured by titrating the acid in a fruit with 0.1N NaOH and then measuring the base needed to reach a pH of 8.1. Finally, overall phenolic compounds and bitterness can be determined by weighing compounds such as alkaloids or glucosides. A ratio or contrast of a fruit's sugar and acid content may provide a relatively easy approximation of taste. The sugar/acid ratio is the definition for this. For an appropriate taste consistency of such fruits, Kader (2002) proposed a minimum soluble solid content (SSC) and a maximum titratable acidity (TA).

- Weight and weight loss percentage measurement

Postharvest water loss significantly impacts fruit quality and is a primary cause of deterioration. Substantial water loss can considerably reduce fresh weight, which may result in economic losses if the product is sold by weight. Even slight moisture loss can cause subtle changes in colour and texture, while reaching a critical moisture loss threshold can lead to more noticeable adverse effects on turgidity, firmness, discolouration, flavour, and nutritional value. Accelerated senescence, increased pathogen invasion, and heightened susceptibility to chilling injury have been reported as weight loss percentage consequences (Kays & Paull, 2004). In general, the quality of most fruits declines rapidly with even small moisture losses, and a loss ranging from 3.0% to 10.0% can render many horticultural crops unacceptable for sale (Robinson et al., 1975).
In postharvest fruit quality assessments, quantifying weight loss percentage is a standard practice to gauge the extent of moisture depletion and its impact on overall produce quality. Typically, the initial mass of the fruit (m_0) is recorded at the onset of storage. Subsequent measurements (m) taken at various intervals are then compared to this baseline to determine how much weight has been lost over time (Kassebi & Korzenszky, 2022).
Weight loss reported as a percentage is a reliable method of evaluating the rate of water loss, variations in metabolic activity, and potential quality deterioration (Sanad Alsbu et al., 2023).

2.1.4. Apple ripening and its assessment

One of the main reasons apples deteriorate and lose a significant portion of their weight during postharvest handling and storage procedures is premature harvesting. Since apples cannot improve their inherent quality characteristics after they are plucked from the tree, selecting the optimal harvest time is crucial for maintaining fruit quality and extending storage time. This harvest timing decision substantially impacts commercially vital characteristics, including fruit size and peel colouration (Valero & Serrano, 2013).

Fruit quality preservation fundamentally depends on two key factors: precise harvest timing and appropriate postharvest storage conditions (Skic et al., 2016). Research indicates that for optimal long-term storage outcomes, apples should be harvested at a mature yet pre-climacteric stage (Rutkowski et al., 2008). Immature harvesting results in quality deficiencies, including inadequate size development, poor colouration, unfavourable flavour profiles (excessive starchiness and acidity), and diminished aromatic qualities. Such prematurely harvested fruits also demonstrate increased susceptibility to physiological disorders, including surface scald, bitter pit, and interior breakdown.

Physically, early-harvested apples exhibit more significant mass loss due to incomplete cuticle development, leading to heightened water loss (Vanoli et al., 2011). These detrimental physiological processes persist even under ideal storage conditions, presenting significant challenges for quality maintenance. On the other hand, harvesting later than the ideal window for maturity causes a decline in sensory quality, which is shown by an unbalanced sugar-to-acidity ratio and textural deterioration (loss of crispness and juiciness) (Watkins et al., 2005).

The ripening process is crucial for consumer appeal, but it also poses serious problems for producers, especially excessive tissue softening, which sometimes causes physical damage and deformation during storage. Because appearance has a direct influence on marketability and customer choice, farmers continue to place a high priority on the visual qualities of fruits.

The last step of fruit growth is ripening, which comes before senescence, the last stage that causes the fruit to deteriorate (Ghosh et al., 2023). Numerous biochemical alterations that alter the fruit's texture, appearance, chemical composition, and organoleptic properties are included in this process. Most fruits accumulate sugars as ripening proceeds, a characteristic well-known to consumers. Similarly, a reduction in acidity typically accompanies ripening in many fruits, such as apples, though exceptions like lemons exhibit contrasting behaviour (Batista-Silva et al., 2018). Regarding phenolic compounds, studies generally indicate a decline during fruit maturation; however, variations in phenolic levels during ripening remain a topic of debate (H. Zhang et al., 2022).

Selecting an optimal ripeness indicator to establish the ideal harvest time for specific post-harvest applications has been extensively researched. Conventional parameters have been evaluated, including skin colouration, firmness, soluble solids concentration, organic acid levels, and starch content (Valero & Serrano, 2013).

Determining fruit ripeness in orchards without causing damage is difficult in agricultural engineering. Maturity levels significantly impact management choices, such as whether to schedule irrigation, when to harvest and how to handle crops after harvest.

By correlating maturity with visual traits such as colour and texture, researchers can refine crop growth analysis, optimise yield forecasting, and develop targeted cultivation strategies (B. Li et al., 2018).

Various imaging technologies have been employed for non-destructive ripeness evaluation, including hyperspectral, multispectral, and visible-light systems (Arendse et al., 2018), with the latter being the most cost-effective. While high-resolution imaging dominates current research, limited studies explore the potential of low-resolution imagery, such as satellite or drone-captured data, for ripening assessment.

Researchers have examined how several fruits' physical and chemical characteristics change when they mature. For instance, a study on the ripening of Golden Delicious apples while storing was carried out in (Cárdenas-Pérez et al., 2017). The green apples were harvested and stored in a room under controlled conditions. Over 40 days, 114 apples were examined. Lightness (L*) and chromaticity (a*, b*) components of the industry-standard CIELAB (Lab*) colour space were used to quantify colour progression. According to the results, L* levels gradually increased until Day 16, stabilised until Day 24, and started falling on Day 32.

2.2. Principles of fruit storage

2.2.1. Critical factors affecting the storage and quality of fruits

Research and field observations over the past four decades indicate that 40–50% of horticultural produce in economically disadvantaged countries is lost before consumption. This issue is primarily attributed to high rates of bruising, moisture loss, and subsequent deterioration during postharvest handling (Kitinoja & Kader, 2002). Fresh food also suffers from diminished market value and nutritional loss, such as loss of vitamins, antioxidants, and other health-promoting compounds. Numerous factors determine the quality of fresh food. The whole influence of everything determines how quickly things deteriorate and decay. Large-scale postharvest losses result from these causes if they are not well handled. Kader claims that almost one-third of all fresh fruits are wasted before consumption (Abdel Kader, 2002). It is further estimated that 30–

40% of total fruit production is lost between harvest and final consumption (Salami et al., 2010). The primary factors contributing to postharvest losses include ineffective temperature control, rough handling, insufficient packaging, and limited awareness of quality preservation techniques (Kitinoja et al., 2011). The quality and shelf life of horticultural products after harvest are primarily influenced by temperature, ventilation, and relative humidity, as these factors play a crucial role in maintaining their freshness and reducing deterioration. Temperature is often the most important environmental factor influencing how long fresh fruits may be preserved (Francis et al., 2012). Since the fruit is still alive, all physiological processes, including respiration and transpiration, continue after it is picked. Nevertheless, the product cannot provide nutrients or water since it is no longer connected to the parent plant.

According to Hofman et al. (2013), low-temperature storage is more successful in preventing chilling damage and enhancing fruit quality. Additionally, low temperatures prevent the development and reproduction of germs that cause spoiling and rotting. Many germs that cause sickness stop growing and replicating at low enough temperatures.

2.2.2. The effect of temperature and humidity on fruit storage efficiency.

Agricultural commodities management and storage have become crucial in the 21st century because of the intricate relationships between respiration, transpiration, and damage from freezing. Relative humidity and temperature must be ideal to reduce post-harvest losses. Storage temperature significantly impacts agricultural goods' shelf life. Figure 2.3 shows how storage temperature affects fruit and vegetable shelf life, with higher temperatures resulting in a shorter shelf life and lower temperatures extending it.

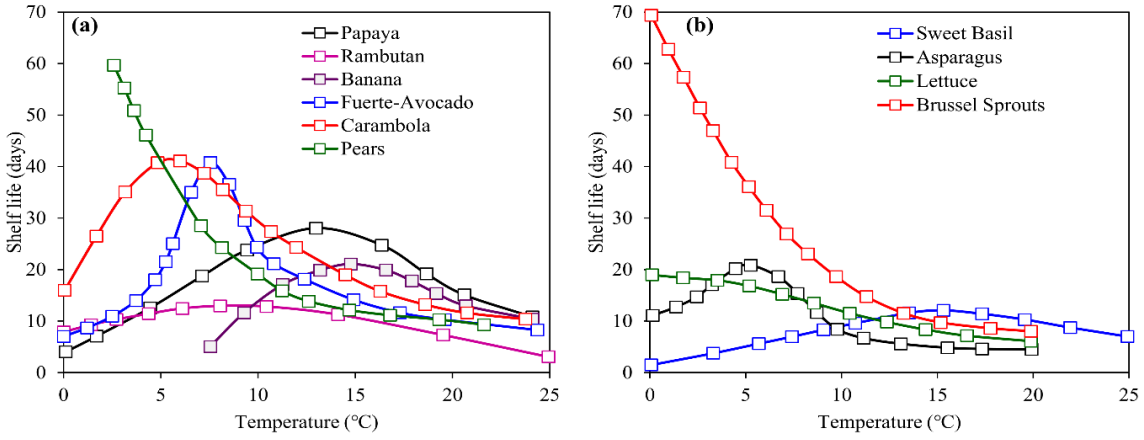


Fig. 2.3. The Influence of storage temperature on the shelf life of some (a) fruits and (b) vegetables (G. Hussain et al., 2022)

Furthermore, the texture, content, and quality of fruits are greatly influenced by temperature (Xu et al., 2006). For example, Figure 2.4 shows how storage temperature affects peaches, asparagus, and Boston-type lettuce quality retention.

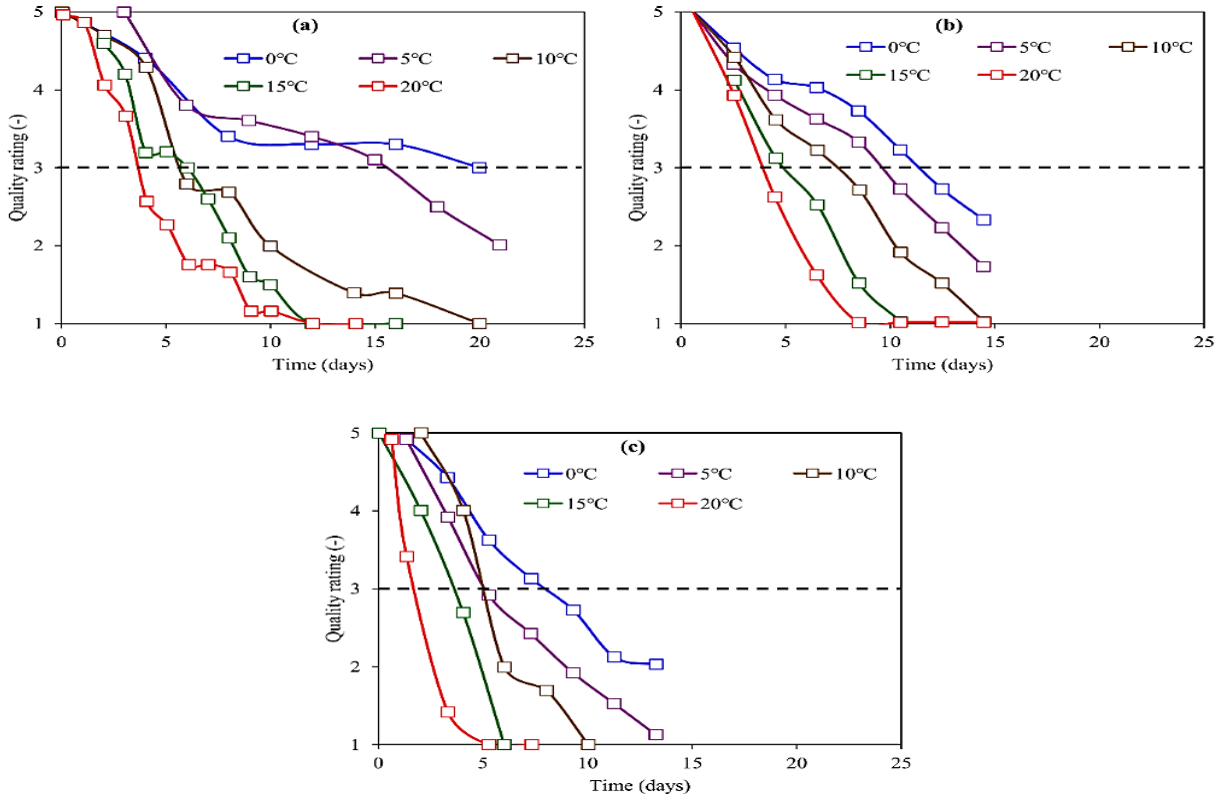


Fig. 2.4. The Impact of Temperature on the Quality of (a) Peach, (b) Boston-type lettuce, and (c) Asparagus, with Dotted Lines Indicating the Acceptable Quality Limits (G. Hussain et al., 2022)

According to Hussain et al. (2022), quality decreased as storage temperature rose. Fruits and vegetables have biological activity and continue to transpire and breathe after harvest. Low oxygen levels are released, and respiration is decreased during storage when the sugar or starch in fruits is combined with oxygen in the surrounding air to form carbon dioxide and water. However, its shelf life shortens when the temperature rises since the respiration rate likewise rises. The effect of temperature on the metabolic activities of different fruits and vegetables is shown in Figure 2.5.

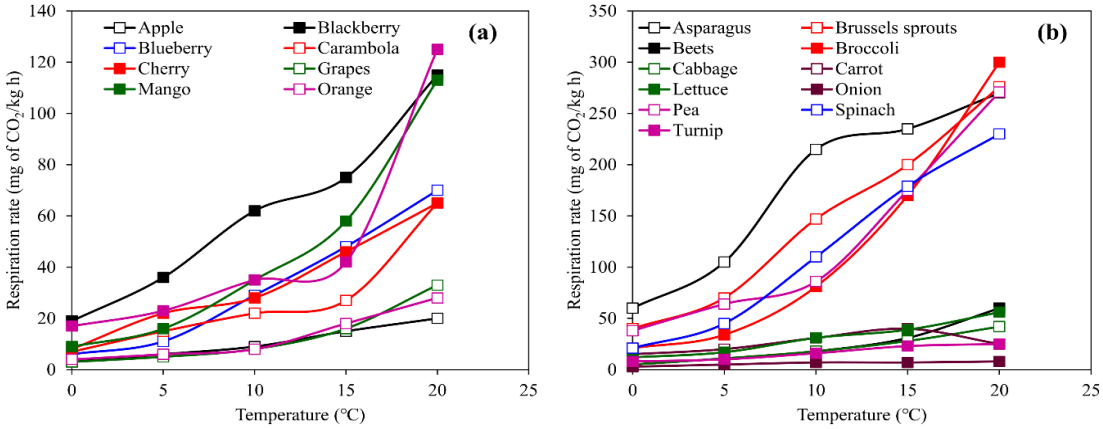


Fig. 2.5. The Impact of temperature on the respiration rate of some (a) fruits and (b) vegetables (G. Hussain et al., 2022)

The rate of respiration increases the respiratory heat in a storage unit. Water loss from harvested products is mainly caused by the degree of moisture in the surrounding air, which can be determined as relative humidity. Agricultural items maintain their nutritional content, flavour, and appearance in high relative humidity. On the contrary, excessive transpiration causes shrivelling at low relative humidity levels (Arah et al., 2015).

According to Enteria et al. (2020), the optimal temperature and relative humidity ranges for fruits and vegetables are -5℃ to 25 ℃ and 85% to 95%, respectively.

2.2.3. Respiratory physiology and its implications for storage

In fruits, respiration is a vital activity that promotes the oxidative breakdown of organic compounds into simpler molecules, such as CO_2 and water, while generating the energy required for essential physiological functions (Bartz & Brecht, 2002). The respiration rate of fruits is affected by several factors, including the age of the plant organ, variety, and plant type (Pérez-López et al., 2014). Additionally, temperature plays a significant role in regulating the respiration rate, with fluctuations in temperature directly impacting metabolic activity(Iqbal et al., 2009). Plasquy et al. (2021) discovered that rising temperatures increase the rate of oxygen consumption. Higher temperatures cause enzymatic protein denaturation and a decrease in respiration rates. For the storage technology, there is a well-known relationship between the fruit's respiration rate and the availability of carbon dioxide and oxygen (East et al., 2009). Fruits breathe less as their concentration of O_2 decreases (P. L. Ho et al., 2020).

The kind and maturity level of the commodity are the internal variables influencing respiration. According to Watson (2016), non-climacteric commodities often have more excellent respiration rates in their early stages of growth that gradually decrease as they mature. Climacteric

commodities likewise have high respiration rates in the early stages of growth, which decrease until a spike happens in tandem with ripening or senescence. However, this trend does not apply to climacteric produce, which follows a different pattern.

Because of the following factors, the respiration curve may change over the storage period following harvest: (1) the product's natural degradation with age, (2) the climacteric products' ripening, and (3) wound metabolism in fresh-cut produce.

Temperature has been identified as the primary external factor influencing respiration rates. Within the typical temperature range encountered in the distribution and marketing chain, biological reactions generally double or triple for every 10°C rise (Barsa et al., 2012). Temperature is critical because food-spoiling microbes' metabolic rates and population growth are effectively zero when below freezing and increase approximately exponentially with temperatures over 0–40°C. This can be quantified in terms of Q10, the factor by which the growth rate increases with every 10°C increase in temperature—the typical Q10 values for microbes that spoil food range between 2.3 and 4.1(Atkin & Tjoelker, 2003). To illustrate the significance of this, consider that with a Q10 value of 3, a single microbe that doubles its population every two days at 4°C will double approximately every hour at 34°C. It could produce around 280 trillion (2.8×10^{14}) descendants in just two days at this higher temperature (Hammond et al., 2015).

Enzymatic denaturation may occur at elevated temperatures, leading to decreased respiration rates. Conversely, increased respiration rate can result from physiological damage caused by extremely low temperatures (Q. T. Ho et al., 2018). Additionally, the concentrations of carbon dioxide (CO_2) and oxygen (O_2) serve as external factors influencing respiration. It is widely recognised that a reduction in overall metabolic activity corresponds to lower oxygen availability, subsequently slowing respiration (Forney et al., 2022).

2.3. Post-harvest storage

2.3.1. Methods and technologies of storage

Over the last few decades, researchers have looked at various solutions to reduce moisture loss during long-term cold storage, including modified atmosphere packing, coating, and chemical and thermal treatment.

2.3.1.1. Controlled atmosphere storage

Low-temperature storage is used in a controlled atmosphere storage process to change the ambient gas composition and purposefully protect crops. In a controlled atmosphere, the amount of oxygen in the surrounding gas is reduced, and the amount of carbon dioxide or nitrogen is appropriately

increased while maintaining a suitably low temperature. Even after harvest, fruits have extremely high respiration rates, and their respiration breaks down long-accumulated nutrients to provide the energy they require for daily activity (Ni et al., 2018).

Consequently, preserved fruits have lower respiration rates, which minimises nutritional loss (Both et al., 2018). Fruits' respiration can be decreased to preserve their original natural look, colour, texture, flavour, and nutrients for extended periods by reducing the oxygen concentration of ambient gases and managing low temperatures and humidity (Cai et al., 2006).

2.3.1.2. Ultra-low oxygen (ULO) storage

An airtight gas cold chamber with a reduced oxygen content (1.0–1.3%), a higher CO_2 content (2.0–2.5%), and a higher nitrogen content is known as an ultra-low oxygen (ULO) cold storage. One advantage of this storage method is that it lowers storage costs by not requiring extra equipment for the storage containers. Additionally, humidity and temperature need to be continuously monitored and adjusted. This storage will prevent and/or reduce fruit deterioration and decomposition after harvest, allow us to transport our product to remote locations, help farmers, and, most importantly, ensure that fruit is available for consumer demand and consumption in the winter and spring with the appropriate quality and flavour.

Along with preserving the apple's quality, including its nutritional and sensory attributes, and reducing or controlling post-harvest diseases, ULO cold store demonstrated a notable increase in the holding shelf life of apple varieties from 90–180 days under common or unregulated storehouses to 210–330 days. In addition to being recognised as an effective storage method for apples, Ultra-Low Oxygen (ULO) storage has demonstrated positive results in maintaining the post-harvest quality and prolonging the shelf life of a variety of different fruit crops, including pears and kiwis (Afif, 2019).

2.3.1.3. Modified atmosphere packaging (MAP)

A preservation method called modified atmosphere packaging (MAP) actively or passively alters the gaseous composition inside a package to extend the shelf life and improve the quality of perishable goods. According to O. J. Caleb et al. (2012), this approach depends on the interplay between the respiration rate of items that are being stored and the gas exchange via the packing material, without the need for further control over the original gas composition. In passive MAP, the appropriate gaseous environment is gradually established within the package by utilising the product's natural respiration and the packaging film's permeability (Charles et al., 2003).

Active MAP, conversely, uses gas scavengers, absorbers, or a quick gas replacement or displacement process to directly alter the interior atmosphere (Farber et al., 2003). To maintain an

ideal gas composition, this procedure uses active ingredients including oxygen regulators, CO_2 absorbers, and ethylene scavengers (Sandhya, 2010). For example, CO_2 absorbers help prevent excessive CO_2 accumulation, which could otherwise reach harmful levels (Kader & Watkins, 2000).

The effectiveness of MAP is significantly influenced by temperature and other environmental conditions, as both the respiration rate of produce and the gas permeability of the packaging film are temperature-dependent. Consequently, maintaining a stable temperature range ensures a consistent modified atmosphere. Even slight temperature variations can alter the internal gas balance, potentially making the product unsafe or unsuitable for consumption (Czerwiński et al., 2021).

A thorough understanding of the three fundamental disciplines underlying modified atmosphere packaging is essential for creating an optimally controlled environment within a package. Polymer engineering involves selecting packaging materials based on their physical, chemical, and gas transmission properties, ensuring the appropriate exchange of gases for product preservation. Produce physiology examines intrinsic and extrinsic factors that influence the respiration rate of fresh produce, allowing for the development of packaging solutions that support extended shelf life and quality retention. Converting technology focuses on the manufacturing and processing of raw materials, including polymers, films, adhesives, inks, and additives, into packaging structures of various formats, ranging from monolayer to multilayer and complex designs, with or without perforations. The integration of these three disciplines enables the creation of innovative packaging solutions that balance environmental sustainability with consumer needs. By leveraging these principles, efficient and effective MAP designs can be developed, promoting resource conservation and product longevity(O. Caleb et al., 2013).

2.3.1.4. Dynamic controlled atmosphere (DCA) storage

Controlled Atmosphere (CA) technologies, especially Dynamic Controlled Atmosphere (DCA) storage, have attracted increasing attention recently (Mditshwa et al., 2018). Biosensors such as respiration quotient (DCA-RQ), ethanol (DCA-ET), and chlorophyll fluorescence (DCA-CF) are used in this sophisticated storage technique to constantly control and modify the gas composition in the storage environment (Mditshwa et al., 2017). Research conducted by Mditshwa et al. (2017) demonstrated that recurrent DCA-CF treatment effectively controlled superficial scald (2%) in Granny Smith apples. These apples were stored in DCA-CF for 16 weeks at −0.5 °C with 95% relative humidity (RH) and underwent a 14-day interval in a regular atmosphere (RA). Furthermore, research has indicated that DCA-CF preservation maintains the internal quality of Gala and Granny Smith apples (ERKAN et al., 2004; Mditshwa et al., 2017) while guaranteeing

the fruit's firmness. A study by ERKAN et al.(2004) found no noticeable differences in the sensory attributes of Greenstar apples stored for ten months in DCA-CF under two oxygen concentration regimes (0.4 and 0.7%) at 1.2 ± 0.2 ℃. Moreover, since chlorophyll fluorescence is linked to the metabolic activity of the fruit, DCA-CF could misjudge the fruit's low oxygen threshold (Weber et al., 2015). The sun-exposed side of the fruit demonstrated higher metabolic activity compared to the shaded side in all three apple varieties, McIntosh, Gala, and Mutsu. This included increased concentrations of soluble sugars, ascorbic acid, and succinic acid in the peel. According to a recent study by Bessemans et al.(2016) Granny Smith apples kept better fruit quality when stored in a Dynamic Controlled Atmosphere with Respiration Quotient (DCA-RQ) environment (0.25–0.4 kPa O_2) than when stored in a traditional low-ethanol Controlled Atmosphere (CA) environment (<0.028 g L−1 in the pulp). Furthermore, after seven days at 18°C, apples stored under DCA-RQ before CA storage displayed fruit quality comparable to those treated with 1-methylcyclopropene (1-MCP). Weber et al. (2015) found that after eight months in cold storage at 1°C, Royal Gala apples held in DCA-RQ displayed superior quality (less flesh disintegration) compared to those in static CA. While dynamic controlled atmosphere with respiration quotient (DCA-RQ) provides several advantages, its effectiveness depends on strictly controlled airtight conditions, which can be challenging to maintain in most Controlled Atmosphere (CA) storage rooms due to the risk of leakage (Wright et al., 2011). An alternative approach, DCA-ET, also referred to as Repeated Low Oxygen Stress (RLOS), determines the low oxygen limit (LOL) by either monitoring headspace composition using sensors or destructively measuring ethanol concentrations in the fruit pulp, with an estimated threshold of approximately 1 ppm. According to research by Veltman et al. (2003), the fruit had fewer skin imperfections and maintained its colour and firmness compared to conventional CA (at 1.2% O_2 and 2.5% CO_2). However, the application of repeated low oxygen stress (RLOS) technology to other significant apple varieties, such as Granny Smith, remains largely unexplored, and this method's underlying mechanisms are still poorly understood.

2.3.2. Cold storage

Cold storage extends the shelf life of agricultural products while ensuring a consistent supply throughout the market. Unpreserved foods can be preserved to keep them from rotting and decaying and to make them available year-round, since the palatability, freshness, and nutritional content can alter with time. It is nearly complicated to enhance the quality of a crop once it has been harvested. The ideal temperature and humidity are essential to extend storage life and preserve the quality of agricultural products. For perishable postharvest output, cold storage

techniques are necessary. Fruits require high relative humidity (80 to 95%) and cold temperatures (0 to 12°C) to reduce respiration and slow down metabolic processes and transpiration rates (Shende, 2018).

A cold chamber is a specific atmosphere where the temperature is very low and specialised instruments and equipment are used. Cold stores are the most essential infrastructure component for storing perishable fruits. Along with guaranteeing the timely supply of goods based on demand and time, the cold storage industry stabilises retail pricing and offers manufacturers and customers other benefits. Consumers benefit from a steady supply of perishable goods at a cheaper price than when they fluctuate. Apples, potatoes, and oranges are commonly kept in cold storage for economic reasons.

Low temperature is the primary technique for extending a fruit's shelf and market life. Cold storage procedures slow the ripening and senescence processes by lowering overall metabolism and controlling respiration rate. The catalytic activity of many enzymes, including those involved in several respiration processes, can be effectively reduced by low temperatures. The storage temperatures for some kinds of fruit that do not require cooling are somewhat higher than their freezing point. Other tropical or subtropical fruits should be stored in a cold environment, usually between 7 and 15°C. The effectiveness of cold storage is also greatly influenced by variables like cooling rates and precooling methods (Valero & Serrano, 2010). Low-temperature storage generally impacts primary and secondary metabolism, upregulates genes that respond to stress, and inhibits the signal transduction of ethylene-related activities (Lin et al., 2018).

2.3.3. Environmental storage conditions

2.3.3.1. Temperature

Temperature is a critical factor influencing moisture loss in fresh produce, as it impacts water potential and humidity in the surrounding environment. This, in turn, increases the water potential gradient between the commodity and its surroundings, thereby accelerating moisture loss (Loveys et al., 2000). On the other hand, a higher temperature results in a higher energy level, which facilitates water evaporation from the exterior surfaces. In contrast, an increase in atmospheric temperature raises the water-carrying potential of the surrounding air, which results in increased moisture loss (Ben-Yehoshua & Rodov, 2002). As the temperature rises, the fruit's skin permeability increases (Nguyen et al., 2006).

The creation of hydrophilic openings in the defensive layers and the reorientation of cuticle lipids have been due to this phenomenon. Furthermore, higher temperatures facilitate nutrient loss in the respiratory system and moisture diffusion through the fruit skin (Bovi et al., 2018).

The findings of studies on apple fruit demonstrate the effect of storage temperature on water depletion. Johnston et al. (2002) found that apples kept at lower temperatures (0–3 ℃) lose less water than those kept at higher temperatures. For example, 'Cripps Pink' apples kept at 0 ℃ lost 2.39% of their water content, while the identical apples at 5 ℃ lost 3.5%. Radenkovs & Juhnevica-Radenkova (2018) showed that the Golden Delicious apples that were stored at 5±1℃ lost 2.9% of their water content after 150 days, while the same cultivar that was stored at ambient conditions (22±2℃) lost 8.3% after 28 days. Therefore, preserving apple quality and minimising water loss requires lower storage temperatures (M. U. Hasan et al., 2024).

Studies on pomegranates (cv. Wonderful) showed that when stored at 5℃ and 7.5℃ for 150 days at 92 % relative humidity, water losses of 27.7% and 45.7 % were recorded (Arendse et al., 2014). After 35 days of storage at 0, 5, 10, and 20℃, respectively, and 96 % relative humidity, Fawole & Opara (2013) found that for pomegranates (cv. Ruby and Bhagwa) stored at 10℃ and 92 % relative humidity for 84 days, water loss was slightly higher than for fruit stored at 5 ℃ and 92 % relative humidity and at 7℃ and 92 % relative humidity. Minor increases in storage temperature have been shown to cause changes in relative humidity and cause moisture loss during storage refrigeration (Shang Ma & Chen, 2003). High temperatures associated with low humidity can cause high respiratory activity in the fruit and increased moisture loss (Opara et al., 2008). To maintain fruit quality and extend shelf life, Saquet et al. (2016) recommend pre-cooling fruits immediately after harvest and ensuring they are stored at optimal temperature and humidity levels throughout the cold chain, encompassing packaging, distribution, and marketing.

2.3.3.2. Relative humidity

Tiny changes in relative humidity, even at a constant temperature, may significantly affect the moisture loss rates of any fresh fruit product(Ben-Yehoshua & Rodov, 2002). Reduced relative humidity causes a more significant drop in water vapour pressure (WVPD) through the fruit membrane, resulting in more moisture diffusion from the fruit to the surrounding air. According to Roudaut and Debeaufort (2010), high WVPD resulted in significant water loss for several plum cultivars kept at room temperature for three days,

Controlling the humidity level during cold storage and on store shelves reduces losses due to post-harvest dehydration. Since most fresh fruit is 85-95% water, a relative humidity of 90-95 % is recommended (Ben-Yehoshua & Rodov, 2002).

According to Tu et al. (2000), fruit held at 65% RH (3.8 and 4.0%) and 95% RH (1.0 and 1.0%) at a constant simulated retail temperature (20 ℃) demonstrated lower water loss (5.3 and 6.0%) than fruit stored at 30% RH. The optimal relative humidity for long-term apple preservation ranges

from 90% to 95%, depending on the cultivar. Fruit kept at a relative humidity (RH) above 95% loses less water and firmness, but it is also more prone to several storage problems (Lidster, 1990). High relative humidity can cause moisture condensation on fruit surfaces. This encourages the growth of microbial communities, resulting in fruit decay (Sandhya, 2010). Therefore, the wetting process must be accurate to avoid spoilage issues in the future.

2.3.3.3. Light

Light is a crucial factor associated with fruits' photosynthesis and photomorphogenic processes. While fruits primarily depend on products from leaf absorption for growth and ripening, their photosynthetic activities can also contribute to more carbon for net photosynthesis, which is essential for seed development (Lytovchenko et al., 2011). The type and intensity of light significantly influence the post-harvest shelf life of fruits and vegetables. Fresh food is sterilised by ultraviolet (UV) and visible light, which helps to increase its shelf life (Cruz et al., 2018). On the other hand, low light intensity postpones the ripening process and increases the post-harvest preservation of basil, lettuce, and spinach compared to dark storage. As a result, the degradation of pigments like chlorophyll and carotenoids decreases, and ATP levels increase (de Bruijn et al., 2020). Light-emitting diodes, or LEDs, have numerous benefits for greenhouse production and food preservation (Md. M. Hasan et al., 2017). They can be placed close to the product as they emit minimal radiant heat and have negligible thermal effects (D'Souza et al., 2015); LEDs present are highly efficient for the food industry. Recent research showed that LEDs help preserve the nutritional value of fruits and vegetables throughout storage (Nassarawa et al., 2021). However, polyphenol oxidase (PPO) is an enzyme that quickly turns apples and other fruits brown; according to some research, fruits exposed to light can activate PPO and develop more brown areas. For example, Manzocco et al. (2009) found that light exposure affects PPO activity in different apple products; they become brown and lose their overall quality. In contrast, apples stored in dark storage exhibited lower enzymatic activity, and their overall quality was maintained. According to Oms-Oliu et al. (2010), pulsed light treatments can alter fresh-cut fruits' antioxidant properties and reduce their nutritional value. However, apples stored in darkness retain higher levels of essential nutrients, as the absence of light minimises light-induced degradation.

The impact of light on microbial growth in stored apples is complex, as different studies have reported varying effects. Specific light wavelengths have been shown to influence the growth of spoilage microorganisms. For instance, Ramos-Villarroel et al. (2011) observed that light exposure reduced microbial populations on fresh-cut fruits, including apples, thereby prolonging their shelf life. However, light also affects the flavour and aroma profile of apples. According to KAHN (2006), light exposure influences the synthesis of volatile compounds responsible for fruit flavour

development. Additionally, research suggests that light can accelerate the ripening process in certain fruit varieties, further highlighting its diverse effects on post-harvest quality; Manzocco and Nicoli (2012) found that light exposure can cause physiological changes, faster senescence, and reduced shelf life for apples.

2.3.3.4. Storage duration

Fruits lose water and weight as they breathe and transpire, absorbing sugar and water stores without replacing them, resulting in wilting and shrinkage. In general, the rate of water depletion peaks at the start of the water deficit pattern and then slows as the storage time increases (Lufu et al., 2020). Compared to the later phase of the water leakage profile, the early phase is the most studied to emulate fruit storage and marketing requirements. Many studies have found a gradual rise in moisture loss with increasing storage time for several fruits (Castellanos et al., 2016; Xanthopoulos et al., 2017).

Susaj et al. (2014)found that the quality criteria of Golden Delicious apples are significantly impacted by the time they are stored after being chilled. Following cold storage, apples were kept for up to 30 days under typical climatic conditions (15±2°C, 75% RH). The study found changes in fruit firmness, juice content, weight loss percentage, and general acceptability throughout this post-cold storage phase. Specifically, the firmness of the apples continued to decrease during the post-cold storage period, with treated apples (2.0% and 2.5% $CaCl_2$) maintaining better firmness than control samples.

A study by Jan & Rab (2012) found significant alterations in apple cultivars' quality over time that impact storage duration. Longer storage times resulted in more weight loss percentage; after 150 days, Red Delicious showed the least weight loss percentage (2.22%). After 150 days, the titratable acidity of the fresh-harvested fruits dropped from 0.67% to 0.38%, with Mondial Gala exhibiting higher acidity. Red Delicious's ascorbic acid concentration and fruit firmness decreased, beginning at 13.12 mg/100g and 5.98 kg/cm^2, respectively. Furthermore, the prevalence of bitter pit and soft rot rose, especially in Red Delicious, which saw the highest levels of these problems after 150 days. Table 2.3 shows the effect of storage duration on several apple cultivars, showing variations in quality criteria over time.

Table 2.3. Effect of Storage Duration on Various Apple Cultivars (Jan & Rab, 2012)

Cultivar	Weight loss (%)	TSS (°Brix)	Total sugar (%)	Titratable acidity (%)
Royal Gala	2.43 ab	11.36	10.81	0.54 a
Mondial Gala	2.40 ab	11.64	10.93	0.55 a
Golden Delicious	2.91 a	11.68	10.79	0.51 a
Red Delicious	2.22 b	12.03	10.98	0.48 b
LSD at $\alpha = 0.05$	0.43	NS	NS	0.05
Storage duration (days)	**Average**	**Average**	**Average**	**Average**
0	0.00 e	9.93 e	9.58 d	0.67 a
30	1.06 d	10.73 d	10.05 c	0.62 a
60	2.60 c	11.39 cd	10.75 c	0.57 b
90	3.25 b	12.25 bc	10.98 b	0.48 c
120	4.05 a	12.70 ab	11.60 b	0.42 d
150	4.53 a	13.08 a	12.33 a	0.38 e
LSD at $\alpha = 0.05$	0.43	0.69	0.60	0.05
Interactions (C×S)	NS	NS	NS	NS

This means that within the same column that shares the same letter(s), do not exhibit significant differences at $p \leq 0.05$, as determined by the Least Significant Difference (LSD) test. Different letters indicate statistically significant differences among values.
NS = Non-significant; C × S = Interaction between cultivar and storage duration; LSD: Least Significant Difference

2.4. Postharvest supply chain

2.4.1. Typical cold chain steps

The phases in a traditional cold chain are shown in Fig. 2.6. The cold chain typically begins when food is pre-cooled to reach the optimal storage temperature. This procedure begins as soon as the fresh fruits and vegetables are harvested. On the other hand, processed dairy products, meat, and fruits and vegetables start as soon as they are processed to guarantee excellent preservation and a longer shelf life. The cold chain stops until the customer stores the food in a home refrigerator, unless food loss happens sooner. Meanwhile, the food can travel through one or more storage and distribution centres before being delivered to retailers, depending on market demand (Mercier et al., 2017), as well as a packing centre and transhipment sites where limited supplier orders are mixed to save money on shipping. The overall length of the cold chain varies greatly depending on the commodity and target market, with some cold chains lasting just a few hours and others lasting months or even years, especially for frozen foods (Mack et al., 2014). The logistics centre is a crucial control point in cold chain management systems since it sorts and mixes shipments obtained from various vendors and plans shipments' departure based on retailer demand, food delivery time, and current conditions. However, each phase in the cold chain significantly affects the food's final quality, and temperature abuse above the food's tolerance level can happen at any moment, resulting in food loss or raising safety issues.

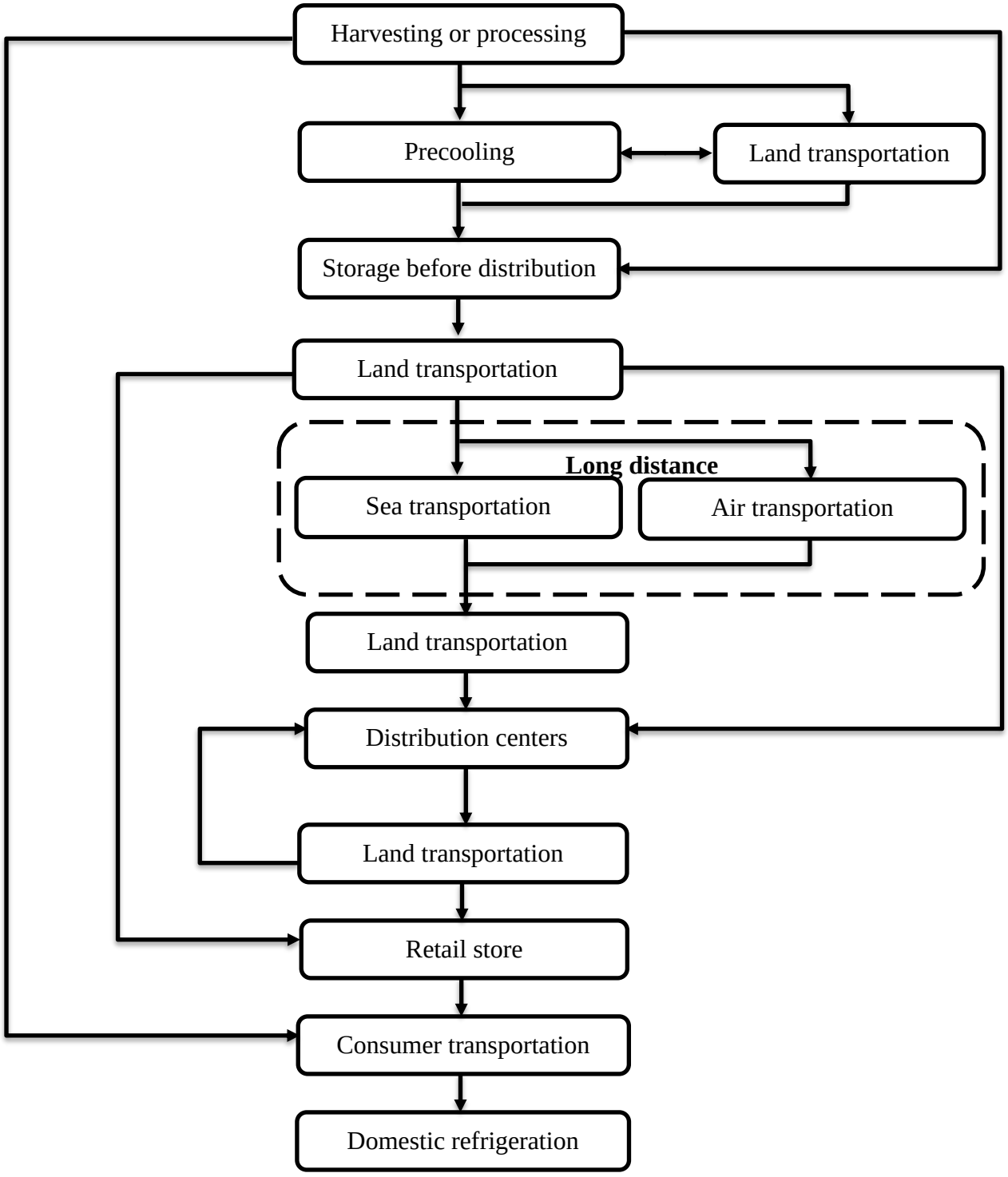


Fig. 2.6. Overview of the main steps in a typical cold chain (Mercier et al., 2017)

2.4.2. Postharvest supply chain quality deterioration

Damage during processing, field manipulation, or shipping, overripe fruit, dried-out fruit, and cold injuries caused by improper storage temperatures, insect damage, and physiological disorders, are

all significant contributors to the loss of postharvest quality up and down the commercial supply chain. These factors influence the fruit's appearance, shape, flavour, and nutritional value.

Fruits are perishable goods that must be appropriately processed to prevent macro- and micronutrient degradation and prolong shelf life (Liu et al., 2020). As a result, during the shipment and postharvest storage cycles, they are often maintained in a preferred low-temperature range by different refrigeration systems. By minimising or stopping microbial growth and enzymatic activity, this method increases productivity, lowers mass loss, and prolongs the shelf life of perishable goods. A series of refrigeration stages that follow these chains can be referred to as the postharvest cold chain for fruits and vegetables (Mercier et al., 2017). Fig. 2.7 shows a fruit and vegetable postharvest cold chain diagram. Food waste in the postharvest supply chain wastes a lot of time and money in packing, shipping, and storage. Between the field gate and storage in a supermarket institution, approximately 25-30% of the world's food supply is lost, mainly due to poor chain management and high deterioration (Shafiee-Jood & Cai, 2016). Food losses are caused by reduced customer standards for quality and protection, especially in developing economies (Gustavsson & Stage, 2011). In postharvest handling, fresh agricultural produce such as fruits and vegetables experiences significant losses, which can reach up to 30% annually (SM, 2019).

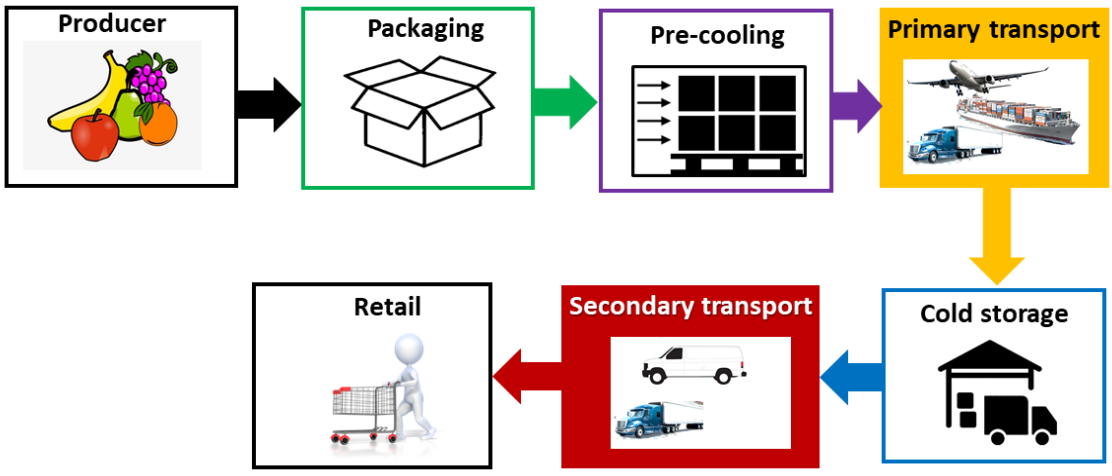


Fig. 2.7. Postharvest refrigerated logistics for fruits and vegetables (Onwude et al., 2020)

Cooling plays a crucial role in enhancing the quality of fresh produce and prolonging its shelf life, ensuring a stable supply in an increasingly urbanised setting (Raut et al., 2019). More than 90% of perishable goods still need to cool (James & James, 2010). More than 20% of perishable food waste is due to a lack of refrigeration or access to electricity (Defraeye et al., 2015). As a result, there is a critical need for sustainable cold chain technologies that allow for more effective resource utilisation, better product quality preservation, and decreased induced food losses. When

strawberries, raspberries, red currants, drupes, cherries, and sour cherries were stored in refrigerated containers at 4°C instead of room temperature storage, weight and nutritional content losses were reduced (Piljac-Žegarac & Šamec, 2011). To ensure consistency and preserve the quality of fresh produce, various food management techniques are becoming increasingly popular. These include intelligent packaging, which uses chemical sensors, temperature and freshness indicators, gas detectors, barcodes, and radio frequency identification (RFID) technology to monitor and preserve product integrity, and active packaging, which also uses oxygen scavengers, ethylene absorbers, and moisture regulators (Ghaani et al., 2016). These various packaging methods are simple to devise, inexpensive to implement, and can help extend food items' shelf life (Defraeye et al., 2015).

The insufficient use of advanced packaging materials, insufficient control equipment, temperature fluctuations, air velocity, relative humidity in cold chain systems, metabolic rate, long delivery times, and fruit and vegetable diversity are all significant contributors to food loss in the postharvest fruit and vegetable supply chain. Temperature and relative humidity within the cold chain structure often exhibit significant fluctuations at various stages during transportation. The rate of change differs among fruits and vegetables due to variations in refrigeration system design, product characteristics, and packaging materials. These variations may affect the fresh produce's ultimate mass loss, overall texture, and remaining shelf life (Duan et al., 2020).

2.4.3. The importance of minimising food loss

Food loss is the decrease in fresh produce meant for humans to consume (Gustavsson et al., 2011). Global fruit and vegetable losses are projected to be 40-50 %, with 54 % occurring during the processing, post-harvest handling, and storage stages (Santos et al., 2020). Nutritional losses are commonly attributable to a loss in the commodity's quality (colour, texture, mass) during storage, transportation, and packaging of perishable agricultural products. These post-harvest handling operations affect farm products' nutritional and sensory content, the mass of fresh produce, and the volume of fresh produce available to consumers. Consumers buy fresh agricultural goods based on biochemical characteristics, including colour, shape, flavour, and nutritional value (Mampholo et al., 2016). In addition to reducing food waste, efficient in-transit monitoring of fresh produce's quality characteristics and environmental conditions during storage and transportation can guarantee that consumers can afford high-nutrient fruits and vegetables (Gordon & Gordon, 2020).

2.4.4. Utilisation of mathematical modelling methods

Modelling expresses phenomena or processes in a way that defines an observable system while predicting or optimising various behaviours, parameters, and conditions (Castell-Palou & Simal, 2011). The use of mathematical simulation in engineering performance design and optimisation is essential. It is possible to predict adverse effects that cause extreme food losses, such as weight loss percentage or changes in quality, using appropriate mathematical models to optimise or monitor cold chain logistics. Due to the complexity and durability of machines and the simplicity and affordability of modelling applications, mathematical modelling approaches are gaining popularity as a substitute for costly and challenging trials in postharvest cold chain activities (Zou & Li, 2020). Over the years, agricultural and food engineering researchers have developed various mathematical models to optimise postharvest cold chain processing. The efficiency of fresh produce has been described using multiple deterministic, stochastic, and kinetic models, such as fluid dynamics, mass loss, and heat and mass transfer during storage and transit (Ktenioudaki et al., 2019).

Mathematical modelling is a common technique in agricultural and food technology (Gorzelany et al., 2022). Precise models enable the prediction of food's physicochemical characteristics and optimum storage conditions. There are two methods for mathematically modelling the mechanical properties of food. The first is grounded on experimental evidence, whereas the second is grounded in the physical properties of the phenomena. This technique is gaining popularity because empirical modelling is easier to construct and more accurate (Moradi et al., 2020).

Mathematical models greatly help agriculture by calculating quantities, forecasting yields, and studying critical agricultural aspects. Karthiayani & Nithyalakshmi (2020) examined the respiration rates of three mango cultivars at various temperatures to create a mathematical model for forecasting metabolic activity during ripening and storage.

Statistical modelling is a standard non-destructive method for estimating fruit volume. Saengrayup & Tansakul. (2009) estimated the volume of plum fruits using fruit dimensions as inputs for regression models and artificial neural networks. All these regression models were very suitable, with an R^2 of 0.93 in this experiment.

Employing a model based on the Levenberg-Marquardt algorithm and the hyperbolic tangent sigmoid transfer function, Ziaratban et al. (2017) calculated the volume of apples with an R^2 of 0.99.

Regression modelling is a fundamental statistical approach used to assess the relationships between dependent and independent variables in domains such as economics, biology, and social sciences. This approach enables trend analysis and prediction (Latha et al., 2024). Measuring the

direction and degree of the connection reveals how predictor changes impact results (Ahn & Loh, 1994).

Regression models come in various forms, including logistic, polynomial, and linear regression. Each modelling technique addresses a specific class of data patterns and relationships. The features of the data and the specific research question under investigation dictate which model is employed (Altman, 1998). Choosing the correct regression model for the dataset is one of the most crucial parts of statistical analysis. The decision will affect the validity of the results (Altman et al., 1994). Regression models are essential to data analysis and predictive modelling.

The statistical method known as analysis of variance (ANOVA) is used to find variations in the means of experimental groups. An ANOVA is justified when several experimental groups are within one or more independent (categorical) variables and one dependent variable (a continuous parametric numerical outcome measure) (Sawyer, 2009).

According to Sawyer (2009), ANOVA measures the connection between the dependent and independent variables and is mathematically based on linear regression and generic linear models. For ANOVA, three generic linear models are available: (i) Only the populations and treatments included in the research can be used to conclude the fixed effects model (Model 1). According to the experimental design, the levels within each component are set. (ii) The random effects model (Model 2) describes random effects within levels and concludes the random variance of a population. The mixed effects model includes fixed and random effects (Model 3).

Following a significant analysis of variance, post-hoc comparison techniques are frequently employed to ascertain which group means vary (ANOVA) (Agbangba et al., 2024).

A standard scientific method for explaining occurrences based on the causality principle under specific, controlled circumstances is experimentation.

Comparing measurement trends between groups is a common step in analysing experimental data (Ruxton & Beauchamp, 2008). A Student's t-test is suitable when the model residuals have a normal distribution, and there are two groups to compare; if not, its non-parametric counterpart is employed. However, an analysis of variance (ANOVA) is used when there are more than two groups to compare, and the necessary criteria are met. To determine whether subgroups are significantly different from one another in the event of significant differences (null hypothesis rejected), additional analysis (post-hoc test) is required (Ruxton & Beauchamp, 2008). Post-hoc tests, sometimes referred to as multiple mean comparison tests, also follow many other statistical procedures, such as the generalised linear model (GLM), the linear mixed effect model (LMEM), and the generalised least squares model (GLS). Numerous post-hoc tests that compare more than two groups may be found in the practical and biological sciences and the behavioural science

literature (Ruxton & Beauchamp, 2008). To use these tests, certain conditions must be fulfilled. For instance, before choosing a post-hoc test, some assumptions need to be fulfilled (Day & Quinn, 1989). Typical conditions include whether or not observations are planned or spontaneous across groups, normality, equality of variance, and parity in the number of groups compared (Day & Quinn, 1989).

2.5. Summary of literature review

This literature review comprehensively explores the critical components of fruit quality, storage principles, and postharvest supply chain management, highlighting their interconnections and impact on minimising food losses. The review begins by defining fruit quality as a multifaceted concept influenced by attributes such as appearance, colour, total soluble solids, and pH, alongside various methods for measuring these characteristics. It also includes the state of fruit ripeness and its analysis, as ripening plays a central role in determining internal and external quality attributes. In addition, the review incorporates research related to non-destructive fruit analysis methods, which are widely used to assess parameters such as colour without damaging the fruit. The review then delves into the principles of fruit storage, emphasising the critical roles of temperature, humidity, and light in determining storage efficacy.

The review further examines postharvest storage methods, focusing on cold storage and environmental storage conditions as practical means of preserving fruit quality by slowing metabolic and microbial activities. It also analyses the postharvest supply chain, detailing the typical steps involved in the cold chain, including precooling, transportation, and storage. It highlights the importance of maintaining consistent temperature control to prevent quality losses. Challenges such as temperature abuse, mechanical damage, and microbial contamination are identified as primary contributors to postharvest losses.

Additionally, the literature highlights innovative approaches to reducing food losses, such as applying mathematical modelling techniques to predict spoilage and optimise storage conditions.

The following points will provide a thorough description of the research gaps, as determined by the literature evaluation, and the main ways in which this study fills those gaps are as follows:

- Interior refrigerator illumination during storage has not been well studied, even though ideal storage temperatures (such as 3°C) and humidity management are well-established. While there is no research on how typical refrigerator lighting impacts Golden Delicious apple quality criteria during storage, most studies specifically employ dark environments or customised LED spectrums.

- Previous studies usually focus on single factors (temperature, humidity, or light). No study has examined the combined effects of storage temperature (3℃, 15℃, 24℃), light exposure (dark vs. regular refrigerator light), and a 12-week length on apple quality deterioration.
- Despite the use of non-destructive technologies (such as colour sensors) for quality tracking, there is no systematic validation of weekly measures (weight loss percentage, Nix Pro colour) with endpoint destructive controls (pH, TSS) for Golden Delicious apples across various storage conditions.

This study is the first to:

- Quantify the cumulative effects of standard fridge lighting on Golden Delicious apples at 3℃ over 12 weeks.
- Compare light/dark exposure at 3℃and compare dark storage at three different temperature: 3℃ 15℃ and 24℃
- Track weekly quality evolution via Nix Pro and weight loss percentage.

To the best of the author's knowledge, this is the first comprehensive research that uses non-destructive monitoring to replicate real storage stresses (different temperature, light and dark storage) over 12 weeks. Golden Delicious apples are one of the most important and best-known apple varieties in the world today. They are particularly subject to quality loss during storage and will benefit directly from the findings in terms of storage optimisation.

3. MATERIALS AND METHODS

This chapter details the materials, equipment, procedures, and methodologies employed in the current study. It encompasses evaluating the quality of Golden Delicious apples under different storage conditions, including preparing apple samples, using specific measurement techniques, and using statistical analysis methods for data interpretation. By thoroughly explaining the experimental design, this chapter lays the groundwork for the reproducibility and credibility of the research findings.

3.1. Measured parameters during apple storage

3.1.1. Storage temperature

The storage experiment was conducted in the machinery and food technology laboratory. The studied storage temperatures were 24±1℃, 15±1℃ and 3±1℃. It is fundamental to control and maintain the correct temperature over time when storing Golden Delicious apples. A data logger has been used to accurately monitor temperature variations inside the storage rooms. This device detects any deviation from optimum storage temperatures.

The Ebro EBI 300 TE (Xylem Analytics Germany GmbH, Weilheim, Germany, EBI 300 + TPH 400, T=-20→+40℃ ± 0.5℃) multi-purpose USB data logger was fitted with an external temperature sensor to record the data. The data logger's internal operating temperature range is between -30℃ and +70℃, and the external measurement range is between -35℃ and +70℃. The logger has an accuracy of ± 0.5℃ for temperatures between -20 and +40℃ and ± 0.8℃ for temperatures outside this range, i.e., very high accuracy. The recorder is fitted with a 50 mm long, 4 mm diameter stainless steel NTC probe, connected by a 1-meter long PVC cable that is water, oil-resistant, and food-safe. With an accuracy of 0.1℃, the device records data accurately and in detail.

Ebro Winlog Pro software was used to configure the data loggers at the outset and initially enabled the recorded data to be downloaded and analysed. The data loggers were set up to record temperature every 5 minutes. They were placed in different locations in each storage room, such as the centre, the entrance door, the cooling unit, and the crates containing the fruit samples, as shown in Fig. 3.1.

Data loggers were employed throughout the storage period to monitor and record temperature variations continuously. After storage, the temperature data were extracted using the Winlog Pro software. Key temperature parameters were analysed to generate temperature profiles corresponding to each logger position, including mean, minimum, maximum, and standard deviation

To ensure measurement accuracy, the calibration of data loggers was verified both before and after the storage period, with any discrepancies either corrected or documented.

Fig. 3.1. The Ebro EBI 300 TE multi-use USB datalogger with external temperature probe

3.1.2. Storage relative humidity

A data logger is an electrical device that records and scans automatically. It enables data to be obtained quickly and efficiently at any measurement time. Data loggers can automatically collect data 24 hours a day, seven days a week.

Relative humidity and variations inside the storage rooms were registered to maintain stable conditions. The Ebro EBI 300 TH multi-purpose USB data logger (Xylem Analytics Germany GmbH, Weilheim, Germany, EBI 300 + TPH 400, T=-20→+40°C ± 0.5°C) was utilised to measure this parameter in real-time during storage. It has a resolution of 0.1°C for temperature and 0.1% RH for humidity. The device is robust and compact, measuring 129 x 33 x 14 mm. It has an IP 20 protection rating and can be used in various storage environments.

The operating range of the device is -30°C to +70°C, with an accuracy of ±0.5°C between -20°C and +40°C. The humidity measurement range is 0% to 100% RH, with an accuracy of ± 3% between 10% and 90% RH.

The software used to analyse the recorded relative humidity data is Ebro Winlog Pro software. External probes were placed in the sample boxes to continuously monitor the relative humidity, as shown in Fig. 3.2.

Fig. 3.2. The Ebro EBI 300 TH Multi-Use USB Data Logger for temperature and humidity measurement

3.1.3. Apple weight and weight loss percentage measurement

Weight loss was measured from the beginning to the end of the storage experiment to understand the physiological responses of apples to different storage temperatures under normal atmospheric conditions. Each sample's weight (g) and weight loss (%) were determined in each storage. The apples' weight before storage was determined to provide valuable data on the apples' initial condition, and it was used to determine the weight loss percentage during the experiment period. All samples underwent weighing procedures before, during, and after storage, and each sample was measured three times to determine its weight loss. Tracking weight loss helps assess the effectiveness of storage conditions.

The change in weight of each apple over time (Δm_a) was calculated by subtracting the final mass (m) from the initial mass (m_0). Using the following formula (Kassebi & Korzenszky, 2022):

$$\Delta \mathrm{m}_a = m_0 - m \text{ (g)} \tag{3.1}$$

The weight loss percentage Δm (%) was calculated using the following equation, where the weight loss is expressed as a percentage of the initial weight (Y. Zhang et al., 2022):

$$\Delta \mathrm{m} = \frac{m_0 - m}{m_0} \cdot 100, (\%) \tag{3.2}$$

where,

m – the mass of apples (in grams) during the storage period (g),

m_0 – the initial mass of the apples (g).

The apple fruit samples were weighed weekly using a precise scale type KERN (KERN&SHON GmbH, Germany, KERN PCB 3500-2, max.: 3500 g ± 0.01 g) to calculate the average fruit weight as shown in Fig. 3.3.

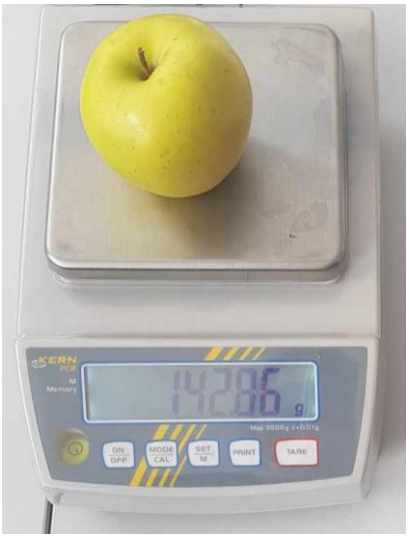


Fig. 3.3. The scale type KERN

3.1.4. Measurement of Apple colour parameters

A NixPro wireless colour sensor (Nix Sensor Ltd., Hamilton, Ont, Canada, NixPro Mini) was utilised to assess the colour parameters of Golden Delicious apples throughout the experiment, as depicted in Figure 3.4. This device features a self-calibrating LED-based light source and an integrated sensor module for precise measurements. The NixPro sensor has a circular design with a 15 mm diameter and employs a 45/0 measurement geometry. It has two high-refractive-index light-emitting diodes (LEDs) designed explicitly for accurate colour reproduction. The instrument has a repeatability of <0.1 DE2000.

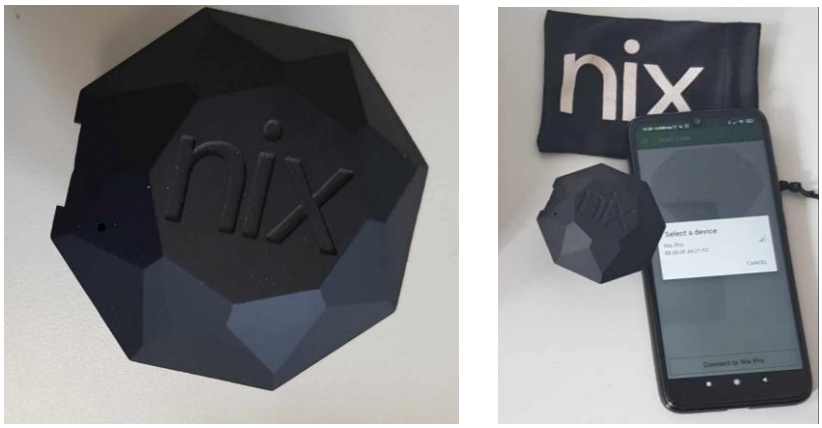


Fig. 3.4. The NixPro wireless colour sensor

The CIELAB colour system within the Nix Pro colour sensor application (App version v1.33, Nix Sensor Ltd., Hamilton, ON, Canada) was utilised for data analysis. The application provided colour measurements in various formats, including RGB, CMYK, HEX, CIELAB, and XYZ values, as illustrated in Figure 3.5. During the experiment, three sets of repeated measurements

were taken from apples using the Nix Pro colourimeter (illuminant D50 and 2º standard observer) for each storage time. The colour was recorded in the CIELAB uniform colour space (Lab), with L* indicating lightness, a* indicating chromaticity along the green (-) to red (+) axis, and b* indicating chromaticity along the blue (-) to yellow (+) axis.

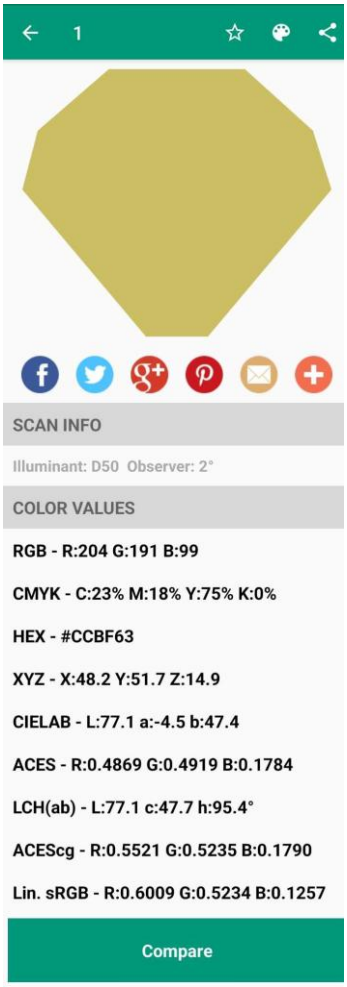


Fig. 3.5. Basic colour data obtained with the NixPro colourimeter

The ΔE colour stimulus difference, also known as colour difference, is a numerical value. The spatial distance between two colour points depicted in colour space can be determined using the spatial Pythagorean theorem. The value of ΔE can be calculated using the following equation (Holzwarth et al., 2012):

$$\Delta E = \sqrt{(L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2} \quad (3.3)$$

In the equation, L^*_0, a^*_0 and b^*_0 represent the colour data of the initial samples, and L^*, a^* and b^* are the measured real-time data.

Where the magnitude of the perceived colour differences is:

0.0 – 0.5 not noticeable,

0.5 – 1.5 barely noticeable,

1.5 – 3.0 noticeable,

3.0 – 6.0 clearly visible,

6.0 – 12.0 large.

Chroma (C*) is a property that expresses how colourful something is compared to something else. In the CIELAB colour space, chromaticity is calculated from a* and b* values. The following relationship describes the definition of Chroma (Holzwarth et al., 2012):

$$C^* = \sqrt{a^{*2} + b^{*2}}, \quad (3.4)$$

The CIELab colour space uses the polar coordinates C* (chroma, relative saturation) and h° (hue angle, angle of the hue in the CIELAB colour wheel) instead of the Cartesian coordinates a* and b*. The CIELAB lightness L* remains unchanged.

The conversion of a* and b* to h° (hue angle) is performed as follows (Holzwarth et al., 2012; Y. Zhang et al., 2022):

$$Hue\ angle = 180 + \arctan(b^*/a^*)/2\pi \cdot 360 \ ; \ a^* < 0, b^* > 0 \text{ and } a^* > 0, b^* > 0 \quad (3.5)$$

The CIELAB hue angle (h°) ranges from 0 to 90 degrees if both a* and b* are positive, from 90 to 180 degrees if b* is positive and a* is negative, 180 to 270 degrees if b* and a* are both negative, and 270 to 360 degrees if b* is negative and a* is positive (Schanda, 2007).

The ΔE is the difference between two colours in the CIELAB colour space, while chroma (C*) indicates its degree of saturation and is proportionate to its intensity. Hue angle (h*) is the qualitative aspect of colour and indicates if a colour is reddish or greenish.

At the end of the storage period, the apples' colour consistently develops a brown hue, regarded as the final stage or limiting colour. Given that the a^* and b^* coordinates corresponding to green and yellow hues are lower than those associated with the brown hue, the colour transformation can be characterised as a saturation process or a form of limited colour development.

3.1.5. Control parameters measurement methods

Destructive analyses were conducted to measure total soluble solids (TSS) and pH at the beginning and end of the storage period to characterise the physiological state of Golden Delicious apples throughout the storage experiment.

At the beginning of the experiment, four apples were measured to provide an initial baseline. In addition, four apples from each storage condition were examined at the end of the storage period.

The juice was made from homogenised apple flesh to determine TSS using a high-speed hand blender (BRAUN, Spain; Model: MR-5550 BC-HC, 600 W + Turbo). The TSS content was measured in triplicate for each sample with a digital refractometer (Ebro Electronic GmbH, Germany; Model: DR-10, range: 0–54% Brix, accuracy: ±0.2%) as depicted in Figure 3.6, and results were expressed as a percentage Brix.

Fig. 3.6. DR-10 type digital refractometer

The same juice was used for pH analysis, which was conducted with a calibrated benchtop pH meter (Electronic Temperature Instruments Ltd., UK; Model: ETI 8100 Plus) as shown in Figure 3.7. Measurements were taken in triplicate for each sample at the initial and final time points to ensure reproducibility.

Fig. 3.7. ETI 8100 Plus type pH measurement equipment

3.2. Preparing apple samples for storage

A batch of Golden Delicious apples was sourced directly from a local farm near Kecskemét, Hungary, in November 2022. The apples had been harvested at the optimal level of maturity, which corresponded to the typical harvest date for marketing. The orchard is situated in a temperate continental climate, characterised by hot summers, cold winters, and annual precipitation of approximately 500–600 mm. The soil is classified as loose sandy with low organic matter content and near-neutral pH, typical of the area's acidic brown forest soils. Nutrient supply included an estimated 30–35 kg of nitrogen per hectare per year, delivered through a combination of compound NPK fertilisers and ammonium nitrate. Calcium was supplied through soil-based amendments and foliar sprays to maintain adequate fruit firmness and prevent physiological disorders. The average yield for Golden Delicious apples in 2022 was approximately 40 tons per hectare.

As shown in Fig. 3.8, a strict selection procedure was carried out in the MATE food technology and machinery laboratory to remove damaged, rotten samples.

Every apple has an identity code (e.g., D03A1, where D03 denotes the darkroom storage at 3ºC and A1 represents the apple), and this allows simple tracking throughout the experiment. All samples were measured three times to create homogeneous groups, with apple size and weight chosen to be roughly identical in each group. This meticulous selection makes it possible to examine every apple in the experiment under the same circumstances, so any found spoiling may be attributable to storage circumstances rather than the fruit themselves.

Fig. 3.8. Preparation of apple samples for storage and experimental analysis

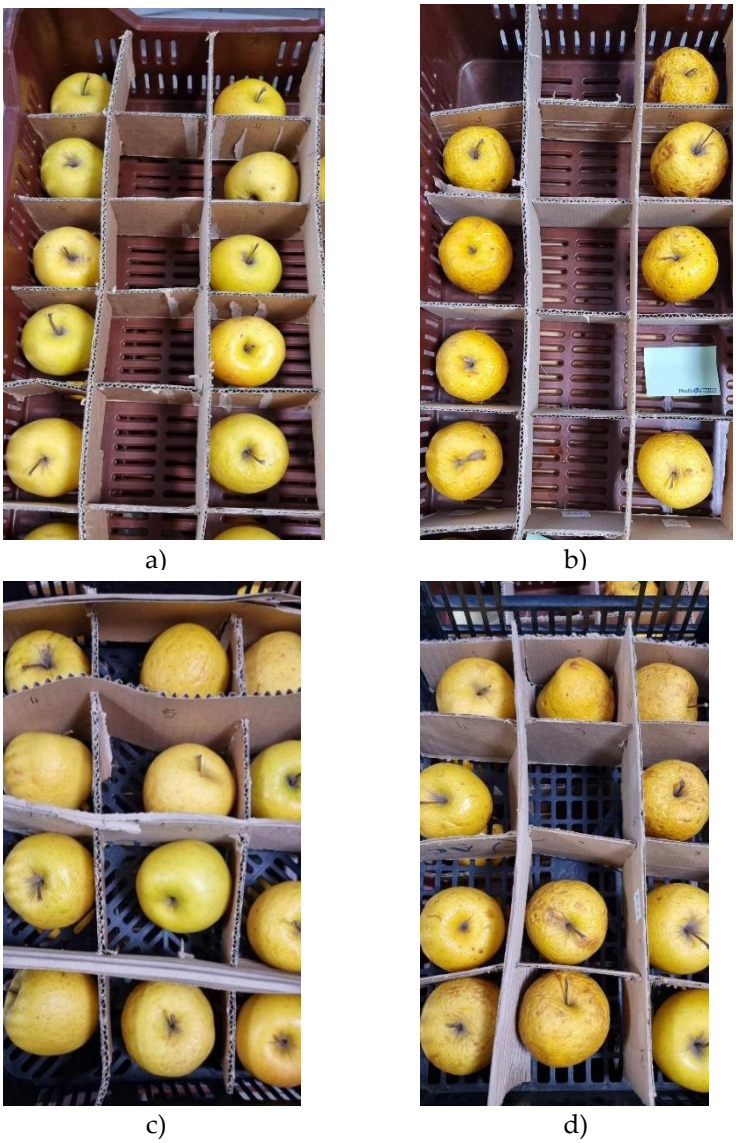
Samples were stored in plastic boxes during the experiment; the choice of plastic boxes is because they do not absorb water vapour, unlike wood boxes, which help to maintain a high relative humidity inside the storage room. The apple separators inside the plastic boxes were made of

cardboard trays, similar to those commonly used in supermarkets for individual apple display; they were used to prevent direct contact between apples and minimise bruising during storage. Once a week, the storage room was opened to minimise initial moisture loss.

3.3. Storage conditions of apples during the experiment

Golden Delicious apples were placed in 4 plastic boxes, each containing 12 apples, as shown in Fig. 3.9. Samples were used for non-destructive measurements, which are weight loss percentage and colour.

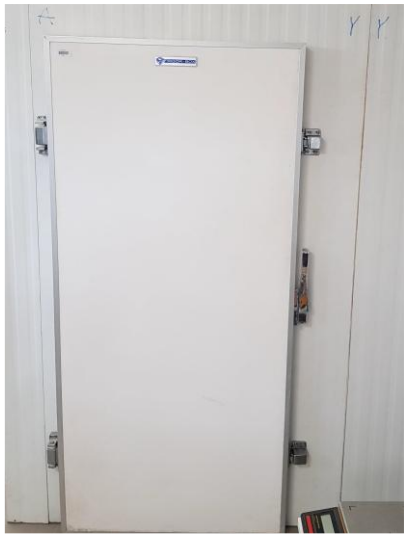
The average weight of the fruit samples was 160 ± 10g, while the mean diameter of the apples measured d=70±2 mm. Each sample underwent three separate measurements for both geometry and weight. A total of 48 apples were stored under various temperature conditions for 12 weeks.



a) b) c) d)

Fig. 3.9. In the middle of the storage period, apples were under different storage conditions:
a) D03 - Dark chamber, +3°C, b) D24 - Dark chamber, +24°C,
c) L03 - Light chamber, +3°C, d) D15 - Dark chamber, +15°C

The first box (box ID is D24) was placed in darkroom storage at ambient temperature (24±1°C) under air relative humidity (RH 60±5%), the second box (box ID is D03) was placed in darkroom cold storage at 3±1°C, under air relative humidity (RH 85±5%) the third box (box ID is D15) was placed at 15±1°C in darkroom storage under air relative humidity (RH 85±5%) and the last box (box ID is L03) was stored at 3±1°C in lightroom cold storage under air relative humidity (RH 85±5%) with a continuous illumination provided by a T8 36W/840 NW fluorescent tube (Kanlux Kft., Győr, Hungary, T8 36W/840 NW, Useful luminous flux of the light source 3350lm, Colour temperature 4000K) as shown in Fig 3.10.



a) D03 - Dark chamber, +3°C

b) D24 - Dark chamber, +24°C

c) L03 - Light chamber, +3°C

d) D15 - Dark chamber, +15°C

Fig. 3.10. Different storage conditions

For L03, D03, and D15 storages, apples were stored in a refrigerated chamber under normal atmospheric conditions. Temperature and humidity were measured using an EBI 300 data logger. (Xylem Analytics Germany GmbH, Weilheim, Germany, EBI 300 + TPH 400, T=-20°C +40°C ±0.5°C).

3.4. Statistical analysis methods

The aim of the study was to observe how the parameters (e.g. Δm; ΔE; Hue angle) of apples observed under different storage conditions (D03; L03; D15; D24) change over 12 weeks. The apples were assigned unique identifiers to ensure no random differences between the individual samples.

A method was used in the statistical analysis that allowed the effect of storage conditions to be measured as accurately as possible while avoiding the problems that may arise when using a traditional statistical procedure. To analyse the effect of time and storage conditions on the parameters of apples, we applied a Linear Mixed Model (LMM). This approach extends the classic Linear Model (LM) by incorporating both fixed and random effects, making it well-suited for handling complex, hierarchical datasets. Fixed effects represent the overall parameter trend across weeks and storage conditions, while random effects account for variability between individual apples. Using residuals, the model isolates the influence of random fluctuations that cannot be explained by fixed effects, offering a more precise understanding of the overall trends. LMMs are particularly advantageous for repeated-measures data, as they handle unbalanced datasets and missing values more robustly than traditional methods.

While a classic ANOVA is a straightforward method, it requires strict conditions like sphericity (equal variance of differences between repeated measurements) and balanced datasets. In our study, these conditions were violated due to missing data (e.g., apples deteriorating under certain storage conditions) and the repeated measures design. By applying ANOVA to the Linear Mixed Model (LMM), we accounted for these challenges. Specifically, the LMM handles missing data and unequal variances more effectively and incorporates random effects to account for variability between individual apples. This ensures a more robust and reliable analysis of the impact of time and storage on the parameters.

Applying ANOVA to the residuals of a linear or mixed model, we are testing if any remaining unexplained variation can be attributed to the factors in the model, such as storage method or week. In the context of applying ANOVA to a linear mixed model, the null hypothesis tests whether the fixed factors (such as storage condition or week) significantly improve the model fit.

H_0: The fixed effect(s) do not explain a significant amount of variation in the response variable beyond what is captured by the random effects and baseline model.

H_1: The fixed effect(s) significantly improve the model by explaining additional variation in the response variable.

This means that ANOVA tests whether the model misses important factors. After accounting for the model's fixed and random effects, it assesses whether there is any additional variance (unexplained by the model) that can be attributed to the factors (e.g., storage method).

The validity of ANOVA results from an LMM depends on several assumptions:

- Homogeneity of residuals: Residuals should have constant variance across the levels of the fixed effects.
- Normality of residuals: Residuals should be approximately normally distributed.
- Independence: Random effects ensure that measurements from the same individual (apple) are not treated as independent, preserving the integrity of the analysis.

By adhering to these conditions, the LMM provides robust statistical inferences even in the presence of complex data structures.

The ANOVA table summarises the significance of fixed effects, and its key columns provide crucial insights (SumSq, Mean Sq, F value, p-value). These columns enable us to identify which factors significantly influence the parameter, guiding further analysis and interpretation of the data.

Post-hoc analyses are essential for examining the specific pairwise differences between the levels of a factor after a significant overall effect has been found in an ANOVA. However, when multiple factors are involved, such as in repeated measures or experimental designs with multiple conditions, the raw means of the groups can be influenced by other covariates, such as time or interactions between conditions. In such cases, Estimated Marginal Means (EMMs) offer a more precise method for these comparisons.

EMMs, or least-squares means, are adjusted means calculated from the model. These means provide a clearer representation of the average response for each group while controlling for the influence of other variables included in the model.

In the context of post-hoc tests, EMMs are used to calculate pairwise comparisons between levels of a factor, such as the different storage conditions in the current study, while accounting for the effects of other variables (e.g., week of measurement). This adjustment leads to more accurate estimates and helps control the family-wise error rate by applying corrections such as the Tukey method, which adjusts the p-values for multiple comparisons.

Establishing a trend is sometimes applied during the analysis. Trend lines (the regression lines) are calculated based on the Estimated Marginal Means (EMM), not the raw data.

EMM represents the means adjusted for other factors (such as storage and week) and reflects the general trend of the data without being influenced by random variation or specific data points. This makes the EMM more suitable for plotting and interpreting the overall pattern in your data. When linear regression is used, the nature of the trends is confirmed by the R^2 and p-values. All analyses were conducted using Excel and R-studio 3.6.0+ software (ggplot2, lme4, emmeans).

4. RESULTS AND DISCUSSION

This chapter presents the research findings and analyses the data from the experimental procedures. Novel conclusions can be drawn regarding the postharvest quality and storage of Golden Delicious apples.

4.1. Effect of storage temperature on Golden Delicious apple properties

The apples were stored under normal atmospheric conditions in a standard refrigerator, where measurements were taken to control temperature and humidity values. The apples were stored at various temperatures with a constant relative humidity, and their weight loss percentage and colour characteristics were studied.

4.1.1. Effect of storage temperature on the weight loss percentage of apples

In this chapter, the percentage of weight loss (Δm) of apples was determined. The initial weight of the apple, recorded at the start of storage, is regarded as the maximum reference value. This weight is then compared to the current week's measurement, expressed as a percentage, to assess changes in weight over time. The apples were given unique identifiers to assign all data to a specific apple.

First, a database was created from the measured data and prepared appropriately for the analysis. During the LMM statistical analyses, the change in the percentage of weight loss (Δm) was examined as a function of the number of weeks of storage (w).

The analysis was completed using the Analysis of Variance Table with Satterthwaite's method. The analysis results for the change in weight loss percentage are presented in Table 4.1. at different storage temperatures (D03, D15, D24), with constant relative humidity.

Table 4.1. Results of ANOVA analysis of the change in Δm value as a function of storage temperature

	Sum Sq	**Mean Sq**	**NumDF**	**DenDF**	**F value**	**Pr(>F)**	**p**
Storage	510.2	255.09	2	32.94	166.56	< 2.2e-16***	<0.01
Week	13046.2	1087.18	12	372.09	709.87	< 2.2e-16***	<0.01
Storage: Week	4100.8	170.87	24	372.08	111.57	< 2.2e-16***	<0.01

Signif. codes: 0 ***, 0.001 **, 0.01 *, 0.05.

The results showed a significant difference ($F=709.87$, $p<0.01$) in the weight loss percentage during the storage duration. Conversely, Apples kept at D24 had the highest weight loss percentage (31.99%), followed by D15, which had an 18.77% loss by the end of the storage period.

The minimum weight loss percentage (5.99%) was recorded for D03. There is a significant difference ($F=166.56$, $p<0.01$) between D03, D15, and D24 storages.

The analysis demonstrated a significant interaction between storage conditions and time. ($F=111.57$, $p<0.01$), which indicates that the weight loss percentage of apples was not the same for D03, D15, and D24 storage, and the influence of storage conditions on weight loss percentage changed throughout the weeks

However, this does not mean that they are different from each other. The difference must be checked with post-hoc tests.

Based on the post-hoc tests performed, it can be stated that the calculated values differ significantly ($p<0.0001$) for all three storage methods (D03; D15; D24). The complete results are provided in Appendix A3. This means that this process can be described by three different time-varying functions.

During 12 weeks of storage, percentage weight loss increased for apples stored in the dark chamber at T=3°C (D03), T=15°C (D15) and T=24°C (D24), as shown in Fig. 4.1.

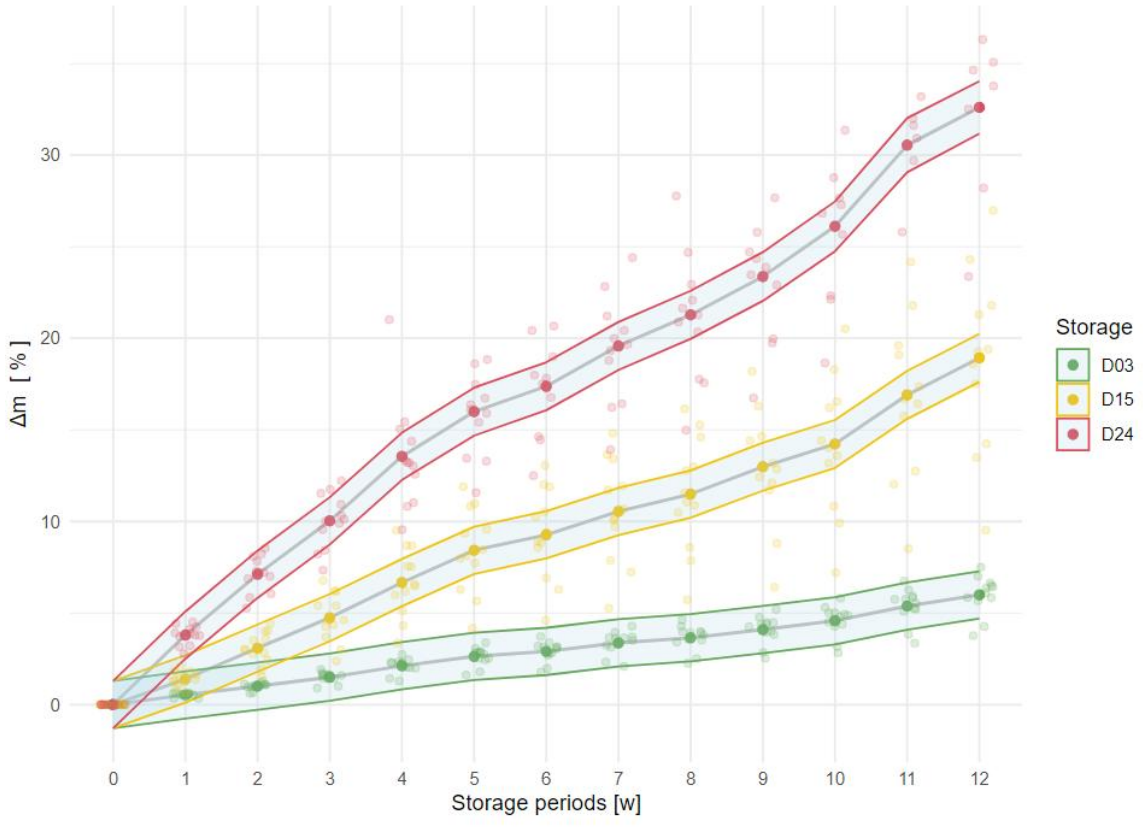


Fig. 4.1. Weight loss (%) of apples stored in a dark chamber (D) at temperatures T=24°C, T=3°C and T=15°C

The relationship between storage duration (w=weeks) and weight loss percentage (Δm) of apples stored at different temperatures is presented by the following equations:

D03; T= 3°C; $\Delta m\ (\%) = 0.4931 \cdot w$ where $R^2 = 0.9865$; $w \in [0\text{-}12]$ weeks; RH85±5% (4.1)

D15; T= 15°C; $\Delta m\ (\%) = 1.5216 \cdot w$ where $R^2 = 0.9911$; $w \in [0\text{-}12]$ weeks; RH85±5% (4.2)

D24; T= 24°C; $\Delta m\ (\%) = 2.7253 \cdot w$ where $R^2 = 0.9772$; $w \in [0\text{-}12]$ weeks; RH60±5% (4.3)

(D03; T= 3°C; w=12; RH85±5% / D15; T= 15°C; w=12; RH85±5% / D24; T= 24°C; w=12; RH60±5%)

To specifically compare storage temperatures (D03, D15) under constant relative humidity, the D24 setting was excluded from this analysis. Results for Δm under these conditions are presented in Table 4.2. The analysis was performed using the Satterthwaite method within an analysis of variance framework.

Table 4.2: ANOVA results for Δm across storage temperatures (3°C and 15°C) in apples.

	Sum Sq	**Mean Sq**	**NumDF**	**DenDF**	**F value**	**Pr(>F)**	**p**
Storage	96.5	96.49	1	21.991	78.995	9.887e-09 ***	<0.01
Week	4143.2	345.27	12	260.018	282.671	< 2.2e-16 ***	<0.01
Storage: Week	1120.0	93.33	12	260.018	76.408	< 2.2e-16 ***	<0.01

Signif. codes : 0 ***, 0.001 **, 0.01 *, 0.05.

The results showed a significant difference ($F=78.995$, $p<0.01$) in weight loss percentage between D03 and D15 during the 12-week storage period.

The results of this work are in agreement with those of Zhang et al. (2022), who obtained similar findings for the weight loss percentage of Golden Delicious apples stored at 4 ±1°C and 20 ± 1°C, with a relative humidity of 80–85%. They found that storage duration and temperature greatly influenced weight loss percentage and peel hardness. The respiration and transpiration of postharvest apples resulted in a decrease in fruit mass and an increase in weight loss percentage as storage time was extended. The fact that the flesh hardness of apples stored at 4 °C decreased very slowly and remained higher than that of apples stored at 20 °C at the end of storage suggests that the lower storage temperature might better preserve apple flesh hardness.

Cold storage helps reduce apples' weight loss percentage by slowing down respiration and transpiration processes, but weight loss percentage will still occur gradually over time. The longer the apples were stored, the more weight they lost. The temperature at which the apples were stored also impacted the weight loss percentage.

Storage conditions, particularly duration and temperature, substantially influence weight loss percentage.

According to P. R. Hussain et al. (2012), if the weight loss percentage exceeds 10%, the fruit may exhibit rotting and shrivelling, resulting in a decline in quality and market value. The findings

showed that apples stored in D15 had a 10% weight decrease after the sixth week, while those stored in D24 reached a 10% weight loss percentage compared to the initial weight by the third week.

Relative humidity was maintained at 85±5% for the D03 and D15 samples, while a lower relative humidity of 60±5% was used for the D24 samples. The differences in relative humidity, particularly in the D24 storage condition, could have influenced the weight loss percentage results. However, the primary aim of the study was to investigate the effect of temperature on weight loss percentage; the D24 setting was used as a conventional control and differences in relative humidity were considered as an additional secondary factor.

Our results show that storing Golden Delicious apples at 3℃ with 85±5 % relative humidity can extend shelf life. In this storage environment, apple ripening is delayed, microbial growth is reduced, and water loss from the apples is reduced.

Conversely, storing apples at higher temperatures, such as 24℃ under 60±5%RH, results in faster ripening, lower quality, and higher vulnerability to spoilage.

4.1.2. Effect of storage temperature on apple colour parameters (L, a*, b*)*

In this chapter, the colour parameters of the apple were determined. The a*, b* and L* values of the CIE Lab colour space were recorded each week with three repetitions. The apples were assigned unique identifiers to assign all data to a specific apple. During 12 weeks of storage, the colour parameters of apples stored in a dark chamber at temperatures of T=3℃ (D03) with 85±5 %RH, T=15℃ (D15) with 85±5 %RH and T=24℃ (D24) with 60±5 %RH were examined.

The a* values increased from the first week (week 0) to the last week for apples stored at D03, D15, and D24. The values increased from -3.83 to -0.98 for D03, from -3.27 to 6.20 for D15, and from -3.24 to 11.32 for D24, as shown in Table 4.3. Higher temperatures lead to more significant shifts in a* value, and the apple is fresh when the a* parameter has a negative value. This is the case for D03 storage until week 12. Starting from week 2 for D24 storage and week 4 for D15, the a* value becomes positive, indicating that the green colour has disappeared and the red has started to emerge. The apple is still fresh if the a* value is below 0. However, if it exceeds 0, it suggests signs of ageing are already visible, signalling that the fruit is no longer fresh, as observed in the tested Golden Delicious apple.

Table 4.3. The a*, b* and L* values of dark room (D) stored apples under different temperatures as a function of the weeks

a* values weeks													
T[°C]	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
3	-3.83	-3.84	-3.68	-3.10	-3.07	-3.07	-2.43	-2.66	-2.61	-1.66	-1.61	-1.08	-0.98
15	-3.27	-3.09	-1.73	-1.26	0.86	1.96	1.82	2.77	3.57	4.15	4.54	5.44	6.20
24	-3.24	-0.79	1.43	2.47	5.48	6.31	5.32	5.97	6.90	7.49	8.87	10.40	11.32
b* values weeks													
T[°C]	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
3	51.09	51.56	52.09	53.31	52.86	52.67	53.12	54.34	54.67	55.33	55.75	55.38	55.13
15	51.44	53.60	55.83	57.41	56.68	56.88	57.01	58.22	57.32	56.91	57.28	56.92	57.57
24	51.47	55.81	57.81	59.26	59.25	58.80	58.69	59.50	58.66	59.41	57.69	58.00	59.07
L* values weeks													
T[°C]	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
3	80.14	79.24	79.05	79.02	78.93	78.62	78.55	78.54	78.52	78.51	77.85	77.83	77.33
15	80.20	79.84	79.65	78.92	77.86	77.41	77.39	76.66	76.64	76.33	75.70	74.31	73.71
24	79.52	79.06	78.80	78.50	77.28	77.04	76.41	76.30	75.76	75.44	73.84	69.82	69.42

The b* values of stored Golden Delicious apples increased from 51.09 to 55.13 for D03 and from 51.44 to 57.570 for D15 from week 0 to week 12, while they increased from 51.47 to 59.07 for D24 storage from week 0 to week 12. The b* value is always positive for the 3 storage. The positivity indicated that it falls within the yellow range, and the higher the positive value corresponding to the more yellow the colour appeared. However, it becomes more noticeable when the temperature is 15°C and 24°C, with b* values much higher than those for D03. As a result, apples stored at 24°C, especially, tend to have a darker reddish-yellow colour faster than the other stored apples.

Apples stored in D24 reached higher b* values than D15 and D03. The high temperature accelerates the appearance of an intense yellow colour.

For D03 storage during the experiment, a* is negative and b* is positive, indicating a yellow-greenish colour of the stored apples. In contrast, for D15 and D24 storage, a* moves from negative (green colour) to positive values (red colour), and b* is always positive (yellow); in these storages, apples' colour shifted towards yellow-red as they ripened.

Different storage temperatures result in varying speeds and intensities of colour change. Higher temperatures, especially D24, cause quicker variations, but D15 causes less variance than D24. Preserving apples at D03 enables a slow colour change; in other words, D03 helps preserve colour quality for a longer period, thereby extending shelf life.

L* values decreased over time. There was a significant decrease in the L* value from week 0 to week 12 for apples stored at D03 and D15, from 80.14 to 77.33 and from 80.20 to 73.71,

respectively. For apples stored at D24, L* values decreased from week 0 to week 12, from 79.52 to 69.42. However, the L* values for apples stored in D03 have slightly reduced. The lightness index (L*) indicates the fruit's degree of freshness. In contrast, a lower L* value indicates a darker fruit that is more likely to turn brown and is more significantly deteriorated than fresh fruit. It can be concluded that storage at high temperatures affected L* values more than storage at lower temperatures.

A study by Cárdenas-Pérez et al. (2017) supports the findings of this study regarding the storage of Golden Delicious apples at high temperatures. They examined the colour changes in Golden Delicious apples stored in the dark at 25 °C and 75% relative humidity over 40 days. They found an initial increase in L* followed by a decline, and reported that the fruit surface became brighter early in storage and darker as ripening progressed. The a* value increased steadily, which indicated a reduction in greenness and a shift toward red and yellow hues, while the b* value also increased. They reported that this indicated enhanced yellowness during ripening. These changes were attributed to chlorophyll degradation and the synthesis of carotenoids and xanthophylls.

Similar results were reported by Zhang et al. (2022), who studied Golden Delicious apples stored at 4 ± 1 °C and 20 ± 1 °C under 80–85% relative humidity. Over time, they noticed that L* decreased and that both a* and b* values increased, along with the formation of brown spots approaching the end of the shelf life. These findings further illustrate the progressive ripening and surface colour changes in apples during storage, influenced by temperature and associated with pigment transformations.

Relative humidity during storage is a critical factor influencing the external colour quality of apples, as it affects surface moisture retention, skin integrity, and physiological responses. According to a study by Lee et al.(2019), on the effect of storage conditions on Royal Gala apples, relative humidity has a significant influence on colour attributes, particularly the L* value, which indicates surface lightness. The study found that L* values decreased during cold storage, and the fruit colour gradually darkened over time. While high relative humidity achieved through perforated polyethene liners did not significantly influence L* during long-term cold storage at 0.5℃ over six months, it contributed to a slower decline in lightness during shelf life at 20℃. Their results suggested that elevated relative humidity can temporarily preserve lightness under ambient conditions. However, the overall trend still showed reduced L* values with prolonged storage, reflecting the natural darkening due to ageing. High relative humidity conditions generally help maintain surface turgor and minimise moisture loss, thereby preserving peel brightness and overall visual quality, including lightness (L*) and related colour parameters.

4.1.3. Effect of storage temperature on calculated colour parameters (C, ΔE, h°)*

Chroma (C*)

This chapter presents the evolution of the colour parameters Chroma (C*), the colour difference (ΔE), and the hue angle (h°), determined according to calculation methods known from the literature. The apples were assigned unique identifiers to assign all data to a specific apple. During 12 weeks of storage, the calculated colour parameters of apples stored in a dark chamber at temperatures of T=3°C (D03), T=15°C (D15), and T=24°C (D24) were examined.

The C* values increased rapidly for apples stored at D15, from 51.60 to 57.98 from week 0 to week 12, and from 51.58 to 58.30 from week 0 to week 12 for apples stored at D24. Over the weeks, the statistical analysis showed a significant ($F=41.5106$, $p<0.01$) difference in chroma values. These findings show that, independent of storage temperature, the period of storage has a significant impact on the intensity of apple colouration. On the other hand, I found that differences in storage temperature lead to notable variations in the intensity of colouration; the storage at different temperatures 3°C, 15°C, and 24°C showed a significant ($F=27.6008$, $p<0.01$) difference in the chroma. For apples stored at 3°C, the highest chroma value was recorded in week 12 of cold storage, with a value of 55.19, as shown in Fig. 4.2. The higher the chroma value, the more intense the colour of the samples will appear to humans. I found that cold storage can delay the increase in chroma value and the appearance of illnesses related to physiological peeling like superficial scald (Leisso et al., 2013). The analysis demonstrates that storage duration and temperature independently affect the chroma of apples, while the difference between them is significant ($F=4.0858$, $p<0.01$) and further influences how colouration evolves. The analysis results for the change in C* are presented in Table 4.4. at different storage temperatures (D03, D15, D24), with constant relative humidity.

Table 4.4. Results of ANOVA analysis of the change in C* values as a function of storage temperature

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)	p
Storage	139.28	69.640	2	33.05	27.6008	8.937e-08 ***	<0.01
Week	1256.83	104.736	12	373.48	41.5106	< 2.2e-16 ***	<0.01
Storage: Week	247.41	10.309	24	373.44	4.0858	1.697e-09 ***	<0.01

Signif. codes : 0 ***, 0.001 **, 0.01 *, 0.05.

The difference must be checked with post-hoc tests.

Based on the post-hoc tests performed, it can be stated that the calculated values differ significantly ($p<0.05$) for all three storage methods (D03, D15, D24). For detailed statistical results, refer to

Appendix A3. This means that this process can be described by three different time-varying functions.

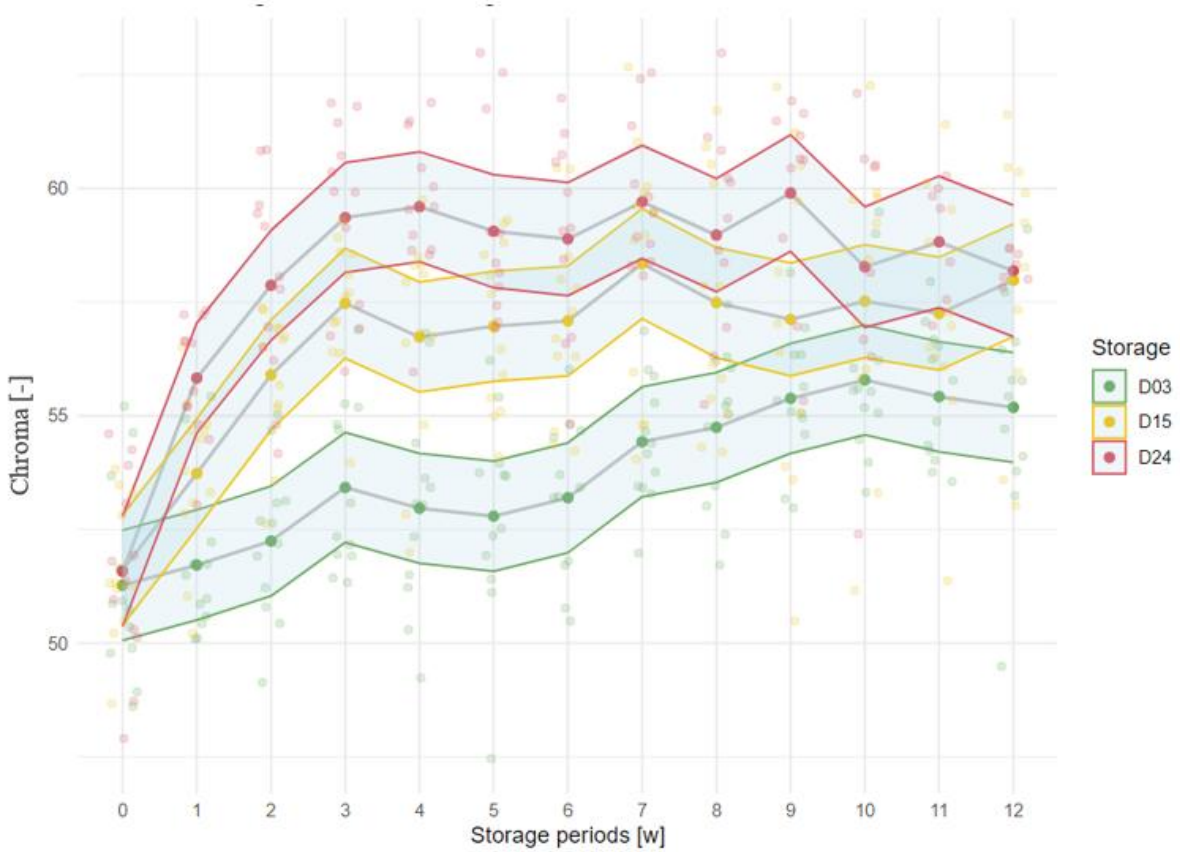


Fig. 4.2. Estimated marginal means of chroma (C*) over storage weeks in a dark chamber (D) at temperatures T=24°C, T=3°C and T=15°C

The evolution of Chroma (C*) of apples stored at different temperatures as a function of storage duration is described by the following equations:

D03; T= 3°C; $C^* = -0.0091 \cdot w^2 + 0.4839 \cdot w + 51.3$ where $R^2 = 0.9237$; $w \in [0\text{-}12]$ weeks (4.4)

D15; T= 15°C; $C^* = -0.064 \cdot w^2 + 1.1507 \cdot w + 52.912$ where $R^2 = 0.8019$; $w \in [0\text{-}12]$ weeks (4.5)

D24; T= 24°C; $C^* = -0.1222 \cdot w^2 + 1.7929 \cdot w + 53.582$ where $R^2 = 0.8001$; $w \in [0\text{-}12]$ weeks (4.6)

(D03; T= 3°C; w=12; RH85±5% / D15; T= 15°C; w=12; RH85±5% / D24; T= 24°C; w=12; RH60±5%)

Colour difference (ΔE)

I calculated the colour difference (ΔE) for the three storages once a week until the end of the storage process, as shown in Fig. 4.3. The obtained results clearly show an increased and visible colour difference in the colour of Golden Delicious apples there is a significant ($F=194.917$, $p<0.01$) difference in the measured ΔE over time. For D03 and D15, ΔE increased from 0 to 6.62. and from 0 to 14.07, respectively, from week 0 to week 12. For apples stored at D24, an increase in ΔE was observed from week 0 to week 12, from 0 to 18.93. The statistical analysis revealed a

significant difference ($F=113.930$, $p<0.01$) in ΔE values between apples stored in D03, D15, and D24. For apples stored at D03, ($\Delta E > 3$) was noticed from week 3 of the storage period. For apples stored at D15, ($\Delta E > 3$) was seen starting from week 1. However, for D24 storage, from the first week, $\Delta E > 5$. This study statistically validated a significant ($F=14.897$, $p<0.01$) interaction between storage temperatures and time.

The analysis results for the change in ΔE are presented in Table 4.5. at different storage temperatures (D03, D15, D24), with constant relative humidity.

Table 4.5. Results of ANOVA analysis of the change in ΔE values as a function of storage temperature

	Sum Sq	**Mean Sq**	**NumDF**	**DenDF**	**F value**	**Pr(>F)**	**p**
Storage	477.2	238.62	2	33.37	113.930	1.231e-15 ***	<0.01
Week	4898.9	408.24	12	374.83	194.917	< 2.2e-16 ***	<0.01
Storage: Week	748.8	31.20	24	374.78	14.897	< 2.2e-16 ***	<0.01

Signif. codes : 0 ***, 0.001 **, 0.01 *, 0.05.

Based on the post-hoc tests performed, it can be stated that the calculated values differ significantly ($p<0.001$) for all three storage methods (D03, D15, D24). The complete results are provided in Appendix A3. This means that this process can be described by three different time-varying functions.

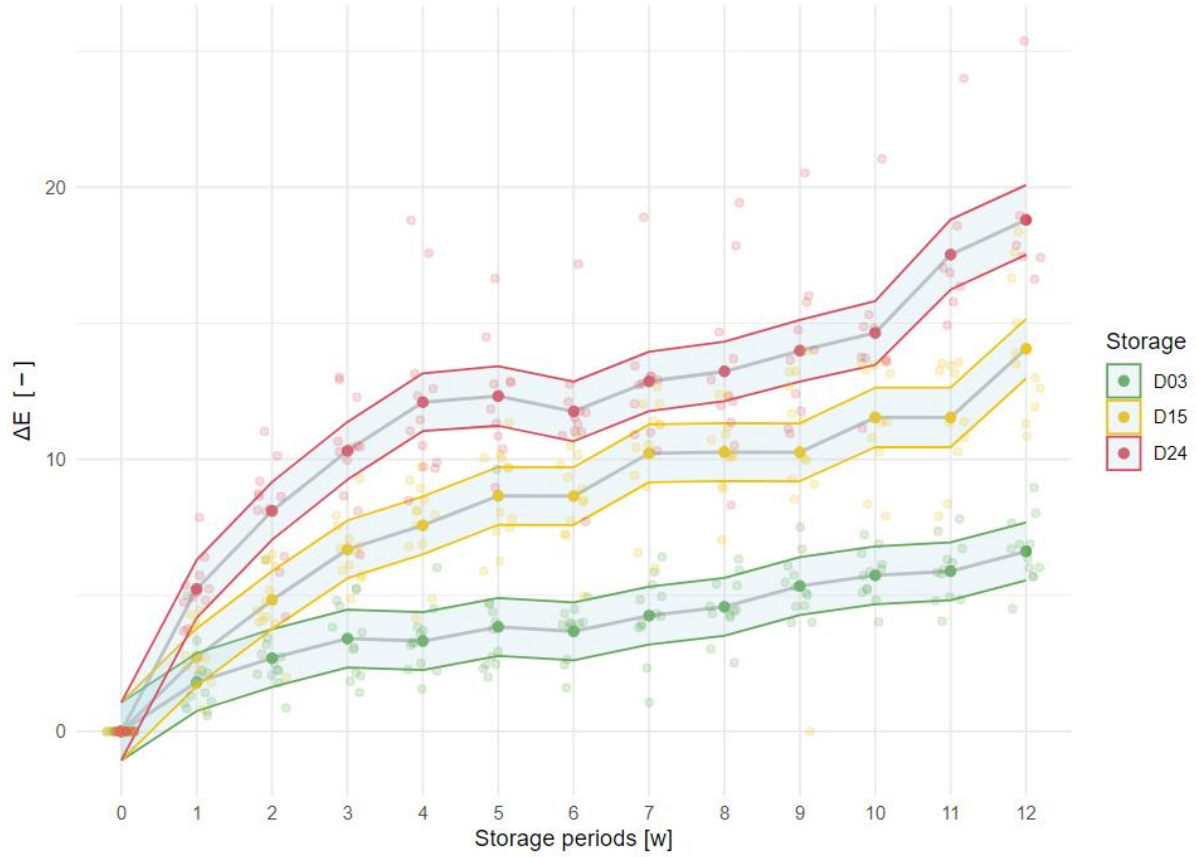


Fig. 4.3. Estimated marginal means of ΔE over storage weeks in a dark chamber (D) at temperatures T=24°C, T=3°C and T=15°C

The relationship between the storage period (w-week) and ΔE of apples stored at D03, D15, and D24 is described by the following equations:

D03; T= 3°C; $\Delta E = 0.5975 \cdot w$ where $R^2 = 0.819$; $w \in [0\text{-}12]$ weeks (4.7)

D15; T= 15°C; $\Delta E = 1.2768 \cdot w$ where $R^2 = 0.8075$; $w \in [0\text{-}12]$ weeks (4.8)

D24; T= 24°C; $\Delta E = 1.6842 \cdot w$ where $R^2 = 0.7189$; $w \in [0\text{-}12]$ weeks (4.9)

(D03; T= 3°C; w=12; RH85±5% / D15; T= 15°C; w=12; RH85±5% / D24; T= 24°C; w=12; RH60±5%)

A study conducted by Xi et al. (2021) about golden delicious apples stored at 4°C, over a storage period of 0, 5, and 10 days, with measurements taken weekly, found that the results showed significant changes in ΔE over time, especially at the early stages. They reported that the increase in ΔE* values reflected a progression in colour alterations, such as decolourisation or browning, which correlated with the apple's ageing process.

To specifically compare storage temperatures (D03, D15) under constant relative humidity, the D24 setting was excluded from this analysis. Results for ΔE under these conditions are presented in Table 4.6. The analysis was performed using the Satterthwaite method within an analysis of variance framework.

Table 4.6: ANOVA results for ΔE across storage temperatures (3°C and 15°C) in apples.

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)	p
Storage	249.87	249.870	1	22.091	130.942	9.358e-11 ***	<0.01
Week	2266.17	188.847	12	261.184	98.964	< 2.2e-16 ***	<0.01
Storage: Week	328.41	27.368	12	261.184	14.342	< 2.2e-16 ***	<0.01

Signif. codes : 0 ***, 0.001 **, 0.01 *, 0.05.

The results showed a significant difference ($F=130.942$, $p<0.01$) in ΔE between D03 and D15 during the 12-week storage period.

Hue angle (h°)

The Hue angle decreased for D03, D15, and D24 over time, as shown in Fig. 4.4. From week 0 to week 12, the values decreased from 94.34 to 90.94 for D03 and 93.66 to 83.30 for D15, respectively. For apples stored at D24, the hue angle decreased from week 0 to week 12 from 93.46 to 78.37.

The change in Hue angle values over the storage (w) weeks was analysed using Linear Mixed Models (LMM) with Satterthwaite's method to analyse variance. The results, which examine the relationship between Hue angle and storage time at different temperatures (D03, D15, D24) under constant and identical relative humidity, are summarised in Table 4.7.

Table 4.7. Results of ANOVA analysis of the change in h° value as a function of storage temperature

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)	p
Storage	117.2	58.583	2	33.11	49.933	1.009e-10 ***	<0.01
Week	3207.9	267.321	12	373.23	227.848	< 2.2e-16***	<0.01
Storage: Week	732.1	30.502	24	373.22	25.998	< 2.2e-16***	<0.01

Signif. codes : 0 ***, 0.001 **, 0.01 *, 0.05.

The statistical results showed that the storage duration significantly ($F=227.07$, $p<0.01$) impacts the hue angle of stored apples, and the storage temperature (3°C, 15°C, or 24°C) significantly ($F=49.933$, $p<0.01$) impacts hue angle. On the other hand, the interaction between storage duration and storage temperature is statistically significant ($F=25.998$, $p<0.01$), and the changes in hue angle over time are temperature-dependent.

Based on the post-hoc tests performed, it can be stated that the calculated values differ significantly ($p<0.001$) for all three storage methods (D03, D15, D24). The complete results are provided in Appendix A3. This means that three different time-varying functions can describe this process.

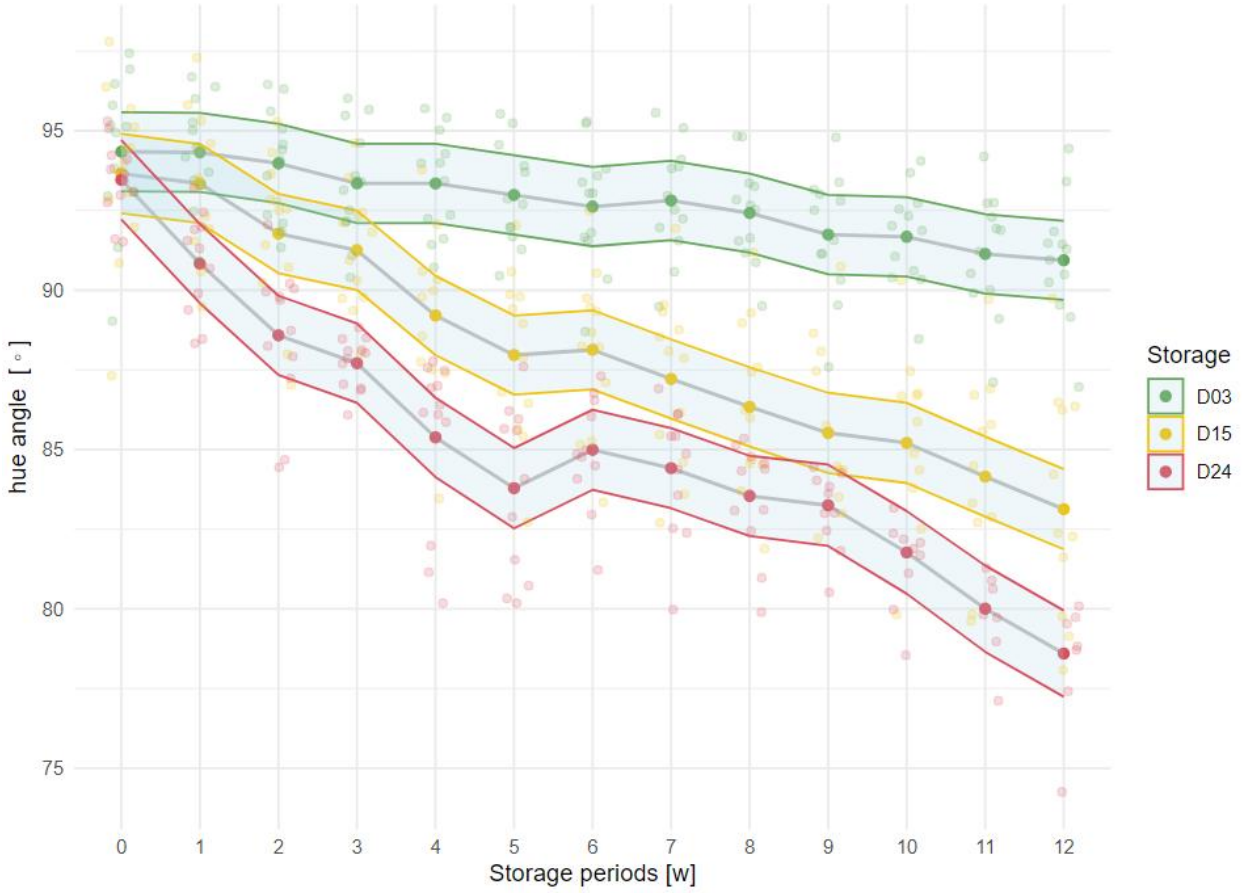


Fig. 4.4. Estimated marginal means of hue angle over storage weeks
at different temperatures (3°C, 15°C, 24°C)

The relationship between the storage period (w-week) and hue angle (h°) of apples stored at D03, D15, and D24 is described by the following equations:

D03; T= 3°C; $h° = -0.2913\ w + 94.484$ where $R^2 = 0.9804$; $w \in [0\text{-}12]$ weeks (4.10)

D15; T= 15°C; $h° = -0.842\ w + 93.356$ where $R^2 = 0.9784$; $w \in [0\text{-}12]$ weeks (4.11)

D24; T= 24°C; $h° = -1.0515\ w + 91.315$ where $R^2 = 0.9239$; $w \in [0\text{-}12]$ weeks (4.12)

(D03; T= 3°C; w=12; RH85±5% / D15; T= 15°C; w=12; RH85±5% / D24; T= 24°C; w=12; RH60±5%)

To specifically compare storage temperatures (D03, D15) under constant relative humidity, the D24 setting was excluded from this analysis. Results for the hue angle (h°) under these conditions are presented in Table 4.8. The analysis was performed using the Satterthwaite method within an analysis of variance framework.

Table 4.8: ANOVA results for hue angle (h°) value across storage temperatures (3°C and 15°C) in apples.

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)	p
Storage	28.01	28.006	1	22.001	28.228	2.477e-05 ***	<0.01
Week	1453.94	121.162	12	260.015	122.124	< 2.2e-16 ***	<0.01
Storage: Week	387.96	32.330	12	260.015	32.586	< 2.2e-16 ***	<0.01

Signif. codes : 0 ***, 0.001 **, 0.01 *, 0.05.

The results showed a significant difference ($F=22.00$, $p<0.01$) in the hue angle (h°) between D03 and D15 during the 12-week storage period.

Apples' visual attractiveness and nutritional value can be affected by variations in the concentration and distribution of pigments, such as chlorophyll and carotenoids, when stored at different temperatures. As apples are climacteric fruits, they continue to ripen even during storage, losing their green colour due to chlorophyll reduction. Chlorophyll synthesis begins to slow down during storage, while new pigments take place. As a result, the apples start to lose their vibrant green colour and shift toward yellow colouring (Gorfer et al., 2022). These changes in pigmentation significantly affect the overall colour of apples.

Higher temperatures could accelerate colour changes over time, while lower temperatures might moderate them. Our findings indicated that D03 storage is more effective in preserving the apple's colour for prolonged periods and helps to prevent significant colour changes. In contrast, D15 and D24 cause rapid colour changes, quickly making the apples less visually attractive.

Zhang et al. (2022) studied Golden Delicious apples stored at 4 ±1℃ and 20±1℃ under 80–85% relative humidity. They found that the apple peel colour showed a decrease in hue angle (H°). However, the changes were slower at 4℃ compared to 20℃, and it was reported that low-temperature storage better preserved the apples' appearance quality.

Cárdenas-Pérez et al. (2017) support the results found in this study regarding the colour development of Golden Delicious apples during storage at high temperature. They found that chroma increased throughout the ripening period, and colour saturation intensified as the apples matured. The hue angle decreased and reflected a shift from dark green to yellow. ΔE increased over time, captured the overall magnitude of colour change and helped to distinguish between ripening stages, including unripe, ripe, and senescent phases. They linked these trends to pigment transformations such as chlorophyll degradation, the accumulation of carotenoids and xanthophylls, and the development of surface browning in the later storage stages.

Although this research primarily focused on how temperature affected the colour development of Golden Delicious apples during storage, the relative humidity may have influenced the observed variations. The lower relative humidity at 24 °C could have contributed to increased water loss and desiccation of the fruit surface, which may accelerate physiological changes such as chlorophyll degradation and skin browning, thus affecting colour measurements.

Lau & Yastremski, (1991)demonstrated that relative humidity during storage plays a critical role in maintaining the quality of Golden Delicious apples, particularly regarding skin colour and firmness. According to their research, lower relative humidity levels, approximately 11% during ripening or storage, were associated with decreased firmness and reduced skin colour retention, resulting in a less colourful and attractive appearance. On the other hand, apples kept in high relative humidity (85% to 95%) showed superior retention of their firmness and green colour.

According to Weber et al. (2012), elevated relative humidity levels, in conjunction with appropriate storage temperatures, positively affect peel colour attributes, particularly hue angle (h°), by delaying surface dehydration and browning. In contrast, low relative humidity environments are associated with increased surface shrinkage, heightened susceptibility to peel disorders, and accelerated degradation of colour quality. Additionally, high humidity might reduce the chance of skin browning. However, if not adequately regulated, extremely high relative humidity can promote microbial growth and the development of skin problems.

4.2. Effect of light and dark storage on Golden Delicious apple properties

The apples were stored under normal atmospheric conditions in a standard refrigerator, where measurements were taken to monitor temperature and humidity values. The apples were stored at the same temperature but under different lighting conditions, and their weight loss percentage and colour parameters were examined.

4.2.1. Effect of light and dark storage on the weight loss percentage of apples

The apple weight loss percentage increased in the dark storage room at +3°C (D03) and in the light storage room at +3°C (L03), as shown in Fig. 4.5.

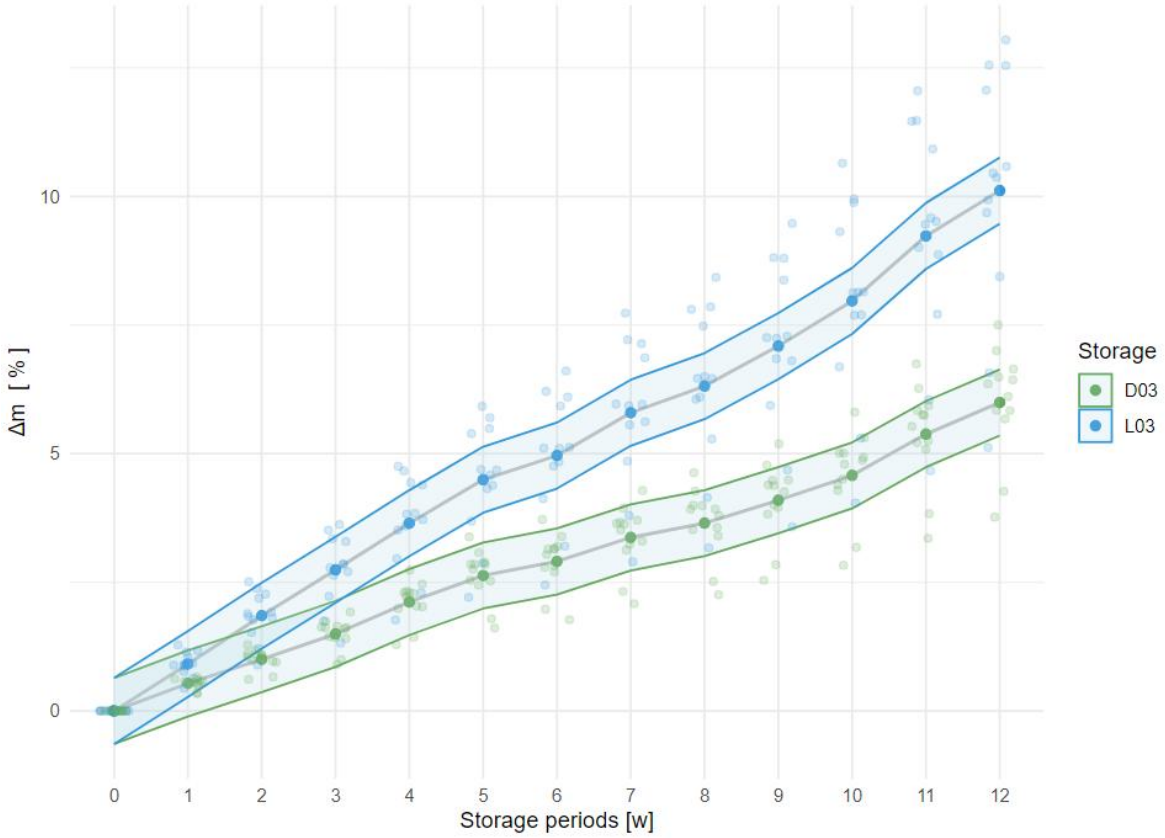


Fig. 4.5. Estimated marginal means of apple weight loss percentage over storage weeks under D03 and L03

The results showed significant (F= 441.041, p<0.01) differences for D03 and L03 in the weight loss percentage throughout the storage weeks. On the other hand, the weight loss percentage was noticeably more significant for apples stored at L03, with a maximum weight loss percentage of 10.11%, while the maximum weight loss percentage for apples stored at D03 attained 5.99%. A fluorescent light source did not significantly affect the stored apples' temperature, as the cooling system maintained the required conditions with its efficient air circulation.

The statistical analysis, using Linear Mixed Models (LMM) with Satterthwaite's method to analyse variance, showed significant (F=29.660, p<0.01) differences in apple weight loss percentage stored at D03 and L03 during the experiment. The storage under light exposure L03 affects more Δm [%] than D03. The latter retained the weight of apples for a more extended period. The weight loss percentage of apples was not the same for L03 and D03 storage, and the impact of storage conditions on weight loss percentage changed for each week. This study demonstrated a statistically significant interaction between storage condition and time (F=29.666, p<0.01).

The results, which examine the relationship between Δm and storage conditions (light L03 and dark D03) at 3℃ under constant and identical relative humidity, are summarised in Table 4.9.

Table 4.9. Results of ANOVA analysis of the change in Δm value as a function of apple storage condition (D03 and L03)

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)	p
Storage	10.04	10.043	1	22	29.660	1.802e-05 ***	<0.01
Week	1792.04	149.336	12	264	441.041	< 2.2e-16 ***	<0.01
Storage: Week	120.54	10.045	12	264	29.666	< 2.2e-16 ***	<0.01

Signif. codes : 0 ***, 0.001 **, 0.01 *, 0.05.

The following equations describe the relationship between Δm and storage duration for apples kept at 3℃ in two different conditions: light (L03) and dark (D03):

L03; T=3℃; $\Delta m\ (\%) = 0.8443 \cdot w$ where $R^2 = 0.9894$; $w \in [0\text{-}12]$ weeks (4.13)

D03; T=3℃; $\Delta m\ (\%) = 0.4931 \cdot w$ where $R^2 = 0.9865$; $w \in [0\text{-}12]$ weeks (4.14)

(L03; T= 3℃; w=12; RH85±5% / D03; T= 3℃; w=12; RH85±5%)

Fruits exposed to light affect stomata cell opening, which increases respiration rates and affects the plant's total metabolism and transpiration (Nassarawa et al. 2021). Weight loss percentage and the firmness change in fruits during postharvest storage are caused mainly by water loss.
In research conducted by Knee et al.(1979), Continuous exposure to light has been shown to speed up ripening in apples by inducing membrane lipid peroxidation. Constant exposure to light might be interpreted as a stressor, as it increases the oxidative state in photosynthetic plant tissues.
Our finding indicates that the efficacy of storage conditions might change over time. Therefore, it is critical to consider storage conditions and duration when preserving Golden Delicious apples.

4.2.2. Effect of light and dark storage on apple colour parameters (L, a*, b*)*

The a* values increased independently of apples stored in D03 and L03 during 12 weeks of cold storage, as shown in Table 4.10. a* values are negative when the apple is still fresh. It is the case for storage D03 until week 12 and L03 until week 10. However, if a* value is positive, it indicates that signs of ageing are visible.
The a* values for D03 are negative, meaning that the apple's colour is green until the end of the storage. However, a* values for L03 tend to move towards positive values. The apples develop some red colour when stored in the presence of light.
Over 12 weeks, b* values for apples kept in D03 and L03 increased from 51.09 to 55.13 and from 50.19 to 55.79, respectively.

Table 4.10. The a*, b* and L* values of stored apples under light (L) and dark (D) storage conditions (T=3°C)

a* values weeks													
Conditions	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
L03	-3.36	-3.02	-2.51	-2.41	-1.89	-1.65	-1.51	-1.22	-1.03	-0.84	-0.26	0.22	0.87
D03	-3.83	-3.84	-3.68	-3.10	-3.07	-3.07	-2.43	-2.66	-2.61	-1.66	-1.61	-1.08	-0.98
b* values weeks													
Conditions	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
L03	50.19	51.91	52.36	53.67	53.28	53.37	53.28	55.30	55.18	55.57	56.26	55.92	55.79
D03	51.09	51.56	52.09	53.31	52.86	52.67	53.12	54.34	54.67	55.33	55.75	55.38	55.13
L* values weeks													
Conditions	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
L03	81.00	80.42	80.13	79.98	79.75	79.70	79.67	79.26	78.65	78.55	78.05	78.14	77.21
D03	80.14	79.24	79.05	79.02	78.93	78.62	78.55	78.54	78.52	78.51	77.85	77.83	77.33

In contrast, the trend for L03 showed that as a* values increased, so did b* values. However, the slight positive a* values indicate a minor shift towards a golden colour with a warmer undertone rather than a visible red. This warm undertone is a part of the ripening process without being necessarily undesirable, depending on the intensity.

D03 better preserves the yellow-green colour typical of Golden Delicious apples, with no transition towards red. The appearance of red is not expected for this variety and could negatively impact market and consumer acceptance.

D03 allows for yellow development while keeping a* negative, which ensures that the apples are visually consistent with what consumers expect from Golden Delicious.

The L* values decreased for Golden Delicious apples stored at D03 and L03 from week 0 to week 12 from 88.14 to 77.33 and from 81.00 to 77.21, respectively. The pigment degradation during storage, caused mainly by carotenoid synthesis and chlorophyll decomposition, is why the colour transitions from green to light green and eventually yellow. The change in L* values results from an enzymatic activity, PPO or polyphenol oxidase, the most widespread enzyme in the browning process of apple flesh. The following equations describe the relationship between L* and storage duration for apples kept at L03 and D03.

In the study by Molina-Corral et al. (2021), Golden Delicious apples were grown under two different environmental conditions that varied primarily in temperature and light exposure. They found that Golden Delicious apples showed decreased L* and hue angle (h°), as well as increased a* and b* values, throughout on-tree maturity under various climatic circumstances. These alterations were attributable to chlorophyll breakdown and carotenoids accumulation.

Pathare et al. (2013) found that colour changes in fruits, especially apples, followed a predictable pattern during storage, with decreased L* and higher a* and b* values.

These changes were attributed to the degradation of chlorophyll and the synthesis of carotenoids and other pigments. The authors also noted that light exposure during storage can accelerate pigment breakdown and browning, while dark storage may help preserve natural colour by reducing photooxidative stress.

Apples naturally turn brown when exposed to air due to a process called enzymatic browning. It occurs when oxygen and certain fruit enzymes react to turn the flesh of apples brown. A study by Supapvanich et al.(2011) discovered that the browning index of apples increases and the lightness (L*) decreases during storage. Besides that, the water loss during storage may be connected to decreased lightness.

4.2.3. Effect of light and dark storage on calculated colour parameters (ΔE, C, h°)*

The chroma (C*), ΔE, and hue angle were determined using L, a*, and b* values. Chroma values vary from 0 (dull/matte) to 60 (highly intense), resulting in higher chroma values viewed as more vibrant by human observers (Pathare et al., 2013).

The highest chroma values were recorded in week 12, measuring 55.82 and 55.19 for apples stored under L03 and D03 conditions, respectively, as illustrated in Figure 4.6.

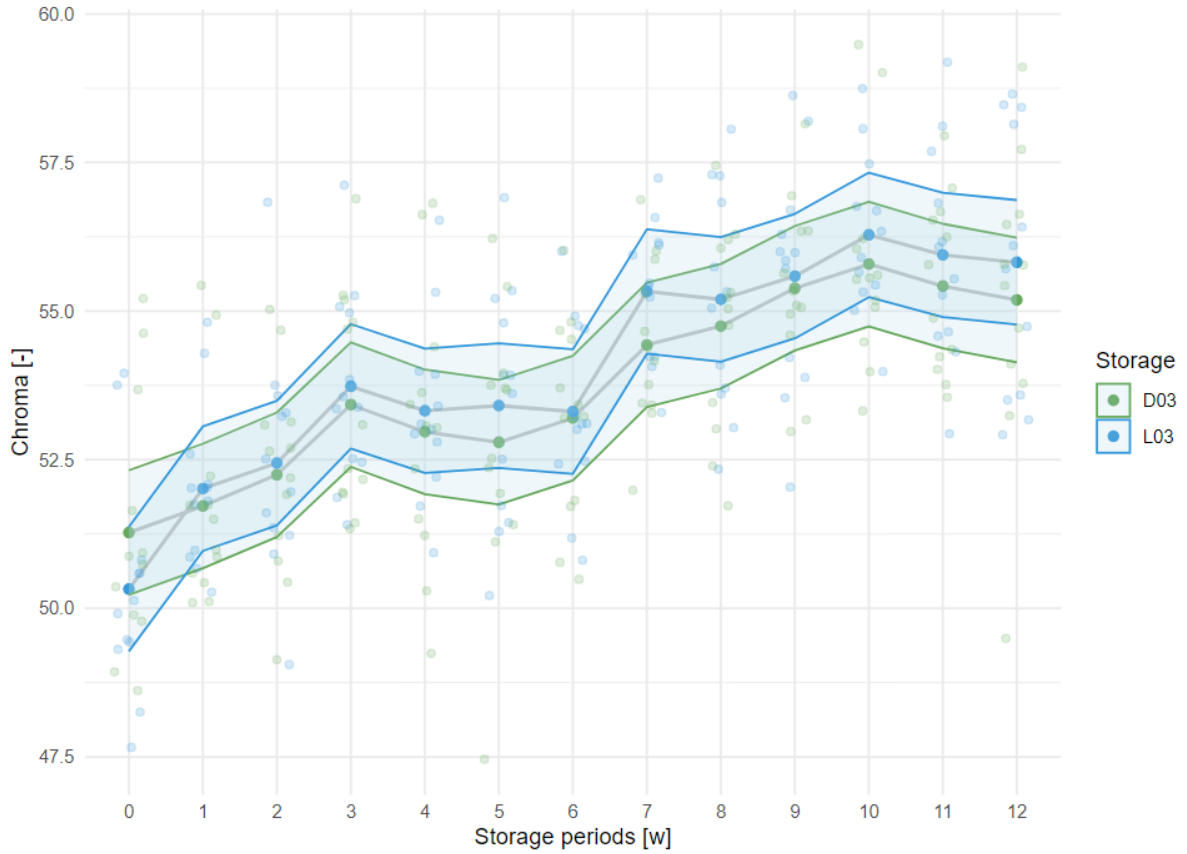


Fig. 4.6. Estimated marginal means of C* over storage weeks under D03 and L03 for apples

Table 4.11. presents the analysis results for the change in C* at different storage conditions (D03, L03), with constant and identical relative humidity and temperature (3°C; RH 85±5%).

Table 4.11. Results of ANOVA analysis of the change in C* values as a function of storage conditions (D03 and L03) for apples

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)	p
Storage	0.36	0.357	1	22	0.2864	0.5979	0.5979
Week	788.30	65.692	12	264	52.7169	< 2.2e-16 ***	<0.001
Storage: Week	13.81	1.151	12	264	0.9236	0.5238	0.5238

Signif. codes : 0 ***, 0.001 **, 0.01 *, 0.05.

The ANOVA results demonstrated that storage duration significantly ($F=52.7169$, $p<0.01$) impacts the chroma of apples stored at 3°C, which undergoes pronounced changes over time. However, there was no significant difference in chroma ($F=0.2864$, $p=0.5979$) between apples stored in light (L03) and dark (D03) conditions. Furthermore, the interaction between storage conditions and time was not significant ($F=0.9236$, $p=0.5238$), which indicates that the influence of time on chroma is independent of storage conditions. The results indicate that chroma values exhibit a similar pattern over time, regardless of the storage conditions.

The relationship between C* and storage duration for apples kept at L03 and D03 is described by the following equations:

L03; T= 3°C; $C^* = -0.015 \cdot w^2 + 0.6389 \cdot w + 51.018$ where $R^2 = 0.9163$; $w \in [0\text{-}12]$ weeks (4.15)

D03; T= 3°C; $C^* = -0.0091 \cdot w^2 + 0.4839 \cdot w + 51.3$ where $R^2 = 0.9237$; $w \in [0\text{-}12]$ weeks (4.16)

(L03; T= 3°C; w=12; RH85±5% / D03; T= 3°C; w=12; RH85±5%)

Next fig. 4.7 illustrates that ΔE increased for apples stored in both the lightroom and darkroom. The highest ΔE values, 8.46 and 6.62 for apples kept at L03 and D03, respectively, were noted in week 12.

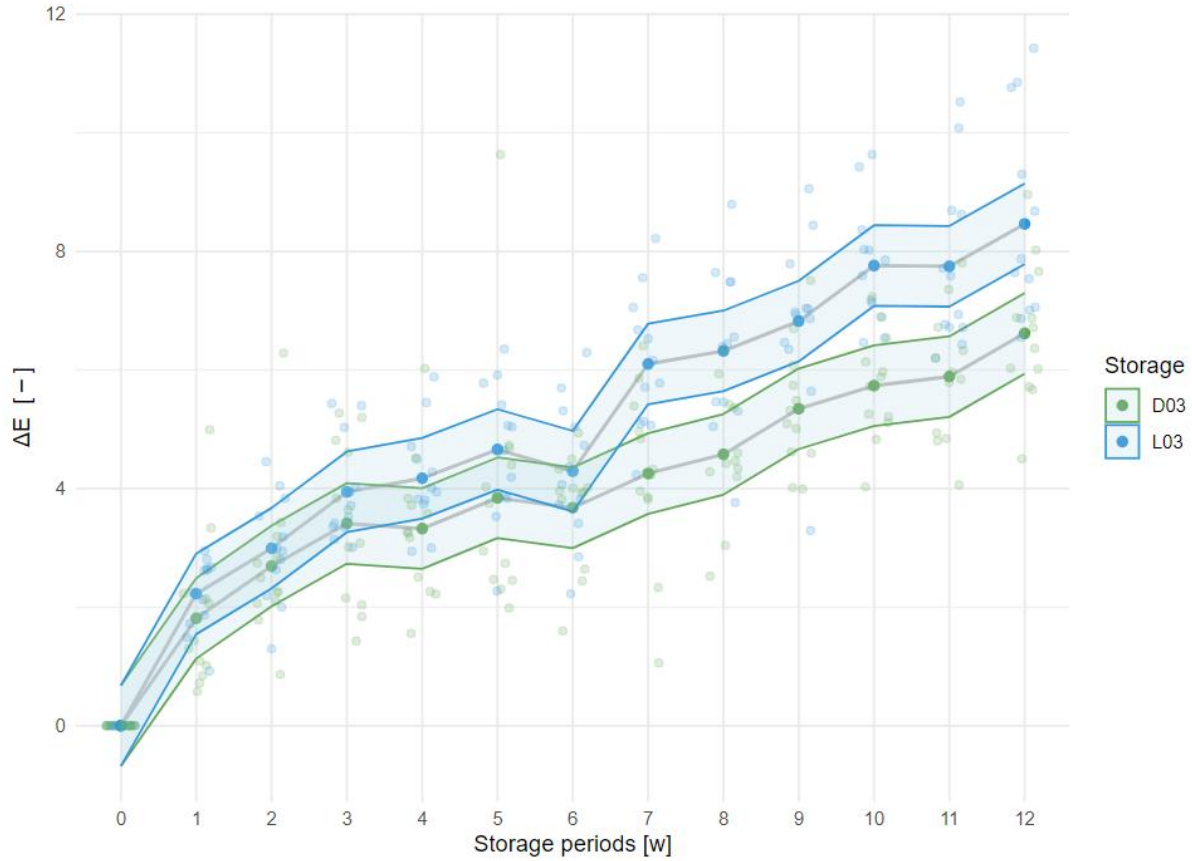


Fig. 4.7. Estimated marginal means of ΔE over storage weeks under D03 and L03 for apples

The analysis results for the change in ΔE are presented in Table 4.12.

Table 4.12. Results of ANOVA analysis of the change in ΔE values as a function of storage conditions (D03 and L03) for apples

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)	p
Storage	10.19	10.187	1	22	11.837	0.002334 **	<0.01
Week	1302.36	108.530	12	264	126.118	< 2.2e-16 ***	<0.01
Storage: Week	36.78	3.065	12	264	3.562	6.278e-05 ***	<0.01

Signif. codes： 0 ***, 0.001 **, 0.01 *, 0.05.

The findings indicate a statistically significant (F=11.837, p<0.01) difference in the ΔE values between apples stored in D03 and L03. According to the statistical findings, time has an essential effect on how the apples' colour changes over weeks, independent of storage conditions (F=126.118, p<0.01). There are three categories for differences in visible colour: highly noticeable when ΔE > 3, noticeable when 1.5 < ΔE < 3, and subtle differences when ΔE < 1.5 (Adekunte et al., 2010). For apples stored at L03, the colour difference (ΔE > 3) is noticeable from the second week of storage. However, for apples stored at D03, a distinct colour difference (ΔE > 3) is observed starting from the third week of storage.

The present study statistically validated a significant ($F=3.562$, $p<0.01$) interaction between storage conditions and time. Storing the apples in L03 or D03 affects how this parameter changes over time.

The following equations describe the correlation between ΔE and the storage period for apples stored at L03 and D03:

L03; T= 3°C;	$\Delta E = 0.7767 \cdot w$	where $R^2 = 0.8555$;	$w \in [0\text{-}12]$ weeks	(4.17)
D03; T= 3°C;	$\Delta E = 0.5975 \cdot w$	where $R^2 = 0.819$;	$w \in [0\text{-}12]$ weeks	(4.18)

(L03; T= 3°C; w=12; RH85±5% / D03; T= 3°C; w=12; RH85±5%)

As shown in Fig. 4.8, the hue angle values for apples stored at L03 and D03 decreased from 93.85 to 89.09 and 94.34 to 90.94, respectively, from week 1 to week 12. This decrease reflected variations in the apple's shade, which changed from light green to yellow during storage.

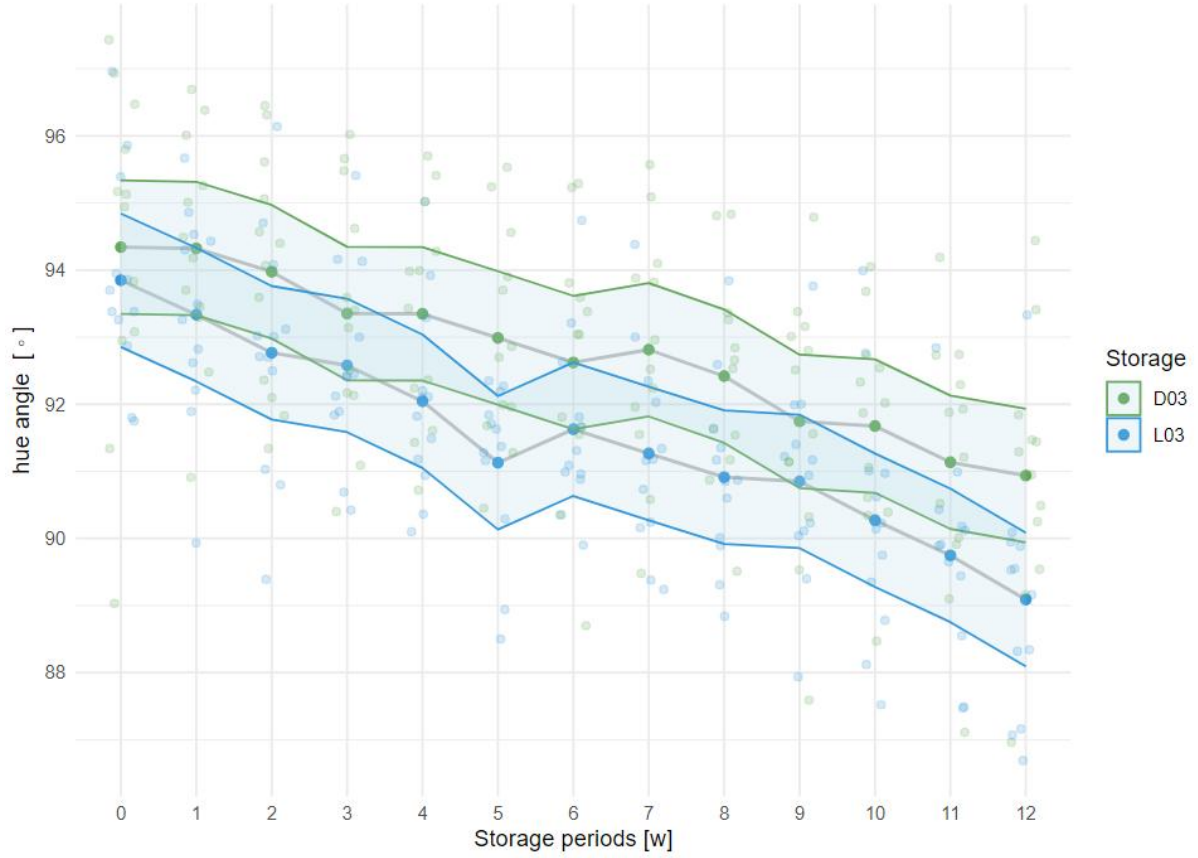


Fig. 4.8. Estimated marginal means of hue angle over storage weeks under D03 and L03 for apples

Table 4.13 shows the results of the analysis of the change in Hue angle (h^o) during apple storage.

Table 4.13. Results of ANOVA analysis of the change in Hue angle (h^o) values as a function of storage conditions (D03 and L03) for apples

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)	p
Storage	1.98	1.983	1	22	3.9037	0.06085	0.06
Week	453.43	37.785	12	264	74.3659	< 2e-16 ***	<0.01
Storage: Week	11.94	0.995	12	264	1.9581	0.02832 *	<0.05

Signif. codes : 0 ***, 0.001 **, 0.01 *, 0.05

The statistical analysis indicated a significant ($F=74.3659$, $p<0.01$) difference between the h^o measured in the first and last weeks, independent of whether the apples are in the dark or the presence of light. On the other hand, the statistical analysis indicated that storage conditions (light vs. dark) had a non-significant effect ($F=3.9037$, $p=0.06085$) on the hue angle. Additionally, the interaction between storage duration and storage condition is statistically significant ($F=1.9581$, $p<0.05$), meaning that the effect of storage duration on the hue angle differs slightly between light and dark conditions.

The following equations describe the relationship between the hue angle (h^o) and the storage period for apples stored at L03 and D03:

L03; T= 3℃; $h^o = -0.3461\ w + 93.582$ where $R^2 = 0.9654$; $w \in [0\text{-}12]$ weeks (4.19)

D03; T= 3℃; $h^o = -0.2913\ w + 94.484$ where $R^2 = 0.9804$; $w \in [0\text{-}12]$ weeks (4.20)

(L03; T= 3°C; w=12; RH85±5% / D03; T= 3°C; w=12; RH85±5%)

According to Fernández-Cancelo et al.(2022), the skin colour of Golden Delicious apples is principally regulated by the amount of flavonoids and carotenoids, which contribute to the yellow hue, and chlorophylls, which are responsible for the green colouration. During storage, the visual appearance of the fruit might vary due to changes in the content and distribution of pigments such as chlorophyll, carotenoids, and anthocyanins, which are affected by environmental conditions (Maskan, 2001). The perceived colour of the fruit is affected not only by pigment concentration but also by the lighting conditions under which it is observed. Recent findings by Jin et al.(2024) demonstrated that postharvest exposure of Golden Delicious apples to white light significantly enhanced the total phenolic and flavonoid content. Among these, flavonols and flavones are particularly associated with developing yellow pigmentation in apple skin. Yellow pigments,

usually flavonoids and carotenoids, become increasingly visible as the fruit ripens because the chlorophyll breaks down. The fruit's appearance changes from green to a more vivid yellow due to this process, giving the peel a brighter colour.

4.3. Relationship between apple weight loss percentage and colour parameters

The outcomes of this research are used to present a relationship study between weight loss percentage and colour parameters, which are hue angle and ΔE, at different storage temperatures. A non-destructive approach to estimating weight loss percentage and evaluating fruit quality during storage is to focus on the colour of the Golden Delicious apple fruit.

As part of the data analysis, a linear regression model was employed to examine the relationship between the two variables.

The findings from the linear regression analysis are presented in Table 4.14 between h^o and Δm.

Table 4.14. The results of the linear regression for the independent variables h^o and Δm in the case of apple storage

	R^2	F	Pr(>F)	p	m	b
L03	0.969	373.3	2E-10	<0.01	-0.411	93.59
D03	0.976	484.7	5E-11	<0.01	-0.582	94.45
D15	0.978	546.1	2E-11	<0.01	-0,553	93.36
D24	0.966	316.8	2E-09	<0.01	-0,426	92.17

(L03; T= 3°C; w=12; RH85±5% / D03; T= 3°C; w=12; RH85±5% / D15; T= 15°C; w=12; RH85±5% / D24; T= 24°C; w=12; RH60±5%)

A correlation study was conducted to investigate the relationship between these factors and the interaction between physical alterations and visual quality after storage.

It was found that a linear correlation exists between weight loss percentage (Δm) and hue angle (h^o) under various storage temperatures. The high R^2 values of the coefficient of determination indicated the strong correlation between weight loss percentage and hue angle.

Due to temperature, humidity, and variations in fruit metabolism, fruits undergo various physiological changes during storage. Fruit colour might vary as a result of these changes. As the fruit ripens, enzymatic and chemical processes can cause changes in skin colour. Our results show a good correlation between weight loss percentage and hue angle during storage, which indicates that as the fruit loses weight, possibly due to water loss, respiration, and transpiration processes, there are concurrent changes in its colour.

During the data analysis, the linear relationship between the variables ΔE and Δm was examined using linear regression.

The results of the linear regression are summarised in Table 4.15.

Table 4.15. Results of the linear regression for the independent variables ΔE and Δm in the case of apple storage

	R^2	F	Pr(>F)	p	m	b
L03	0.972	377.4	7E-10	<0.01	0.672	1.789
D03	0.973	393.4	6E-10	<0.01	0.848	1.614
D15	0.96	264.3	5E-09	<0.01	0.579	3.294
D24	0.936	145.2	3E-07	<0.01	0.414	4.766

(L03; T= 3°C; w=12; RH85±5% / D03; T= 3°C; w=12; RH85±5% / D15; T= 15°C; w=12; RH85±5% / D24; T= 24°C; w=12; RH60±5%)

The slopes of the trendlines indicate the rate of colour change per unit of weight loss percentage. The highest slope was observed under D03 storage (0.848), indicating that weight loss percentage correlates most strongly with colour change in dark storage at 3°C. Weight loss percentage is less significantly correlated with colour change in D24 storage, where the slope was lowest (0.414)

D24 and D15 storages had higher intercepts compared to L03 and D03. Apples kept at higher temperatures changed colour more and lost less weight. The temperature has a significant effect on how quickly colour deteriorates. Weight loss percentage was more directly correlated with L03 and D03 storage, which was also strongly correlated with colour changes. Even at reduced rates of weight loss percentage, D24 storage, however, resulted in much quicker and more significant colour change.

The observed correlation between weight loss percentage and colour degradation in postharvest Golden Delicious apples aligns with findings from Watanabe et al.(2018), who demonstrated a strong positive relationship between weight loss percentage and colour changes (ΔE and chroma) in Shine Muscat grapes under low humidity storage. Their study attributed these correlations to water loss-induced reductions in cellular turgor pressure, which disrupt tissue integrity and accelerate enzymatic browning via polyphenol oxidase activity, alongside chlorophyll degradation. They established predictive equations for ΔE and chroma using weight loss percentage data, finding high R^2 values (R^2 = 0.81–0.94), which demonstrated the validity of this relationship.

Similar results were reported by Lufu et al. (2023), who found a robust linear correlation (R^2 = 0.936–0.991) between weight loss percentage and total colour difference in pomegranate fruit under various packaging and waxing treatments. The authors attributed this relationship to water loss-induced degradation of surface pigments, leading to visible changes in peel colour. This supports the physiological basis for using weight loss percentage as an indirect predictor of colour change during storage in fruits such as apples.

4.4. Control parameters results

In this study, Golden Delicious apples exhibited significant variations in total soluble solids (TSS) after 12 weeks of storage under various conditions, as shown in Table 4.16. The fruit TSS is a critical quality parameter associated with texture and composition (Peck et al., 2006).

Apples stored at D03 exhibited a moderate increase in TSS from 12.00 to 13.13 °Brix. In comparison, those in L03 exhibited a slightly higher rise from 12.00 to 13.63 °Brix, suggesting that light exposure may accelerate sugar accumulation even at low temperatures. After storage at D15, TSS increased significantly from 12.00 to 14.70 °Brix, indicating increased metabolic activity at this intermediate temperature. The most notable change occurred at D24, when the TSS rose to 16.67 °Brix due to moisture loss at high temperatures and rapid starch-to-sugar conversion. Previous research has shown that starch hydrolysis, respiration, and water loss contribute to TSS changes during storage (Duque et al., 1999). Higher TSS levels at higher storage temperatures (D15, D24) correspond to the concept that higher conditions promote sugar accumulation, possibly at the cost of texture and acidity retention (W. Li et al., 2024; Łysiak, 2014). Even at 3°C, apples showed substantial TSS increases, indicating continuous metabolic activity despite cold suppression (Carrín et al., 2004).

Table 4.16. pH and TSS at the beginning and end of apple storage

	pH [-]		**TSS [°Brix]**	
Storage	week 0	week 12	week 0	week 12
D03	3.88	3.89	12.00	13.13
L03	3.88	3.94	12.00	13.63
D24	3.88	5.00	12.00	16.67
D15	3.88	4.18	12.00	14.7

(L03; T= 3°C; w=12; RH85±5% / D03; T= 3°C; w=12; RH85±5% / D15; T= 15°C; w=12; RH85±5% / D24; T= 24°C; w=12; RH60±5%)

Table 4.16 presents pH measurements in Golden Delicious apples under four distinct storage conditions at the beginning and end of storage over 12 weeks. All treatments began with identical initial pH values (3.88). However, the final pH measurements revealed significant changes depending on the storage conditions.

D24 storage showed the most significant pH elevation, which could be related to accelerated metabolic consumption of organic acids. This conclusion is consistent with accepted postharvest physiology principles, which state that higher temperatures enhance respiratory activity (Clark et al., 2003; López et al., 2005).

On the other hand, D03 storage maintained near-stable pH levels. The slight but significant increase in L03 storage implies photochemical influences on acid metabolism, possibly through light-activated enzymatic pathways (Khan et al., 2012).

Intermediate storage at D15 produced the expected results, with moderate pH elevation consistent with previous work on apple acid metabolism (Ghafir et al., 2009).

4.5. New scientific results

In this chapter, I formulate new scientific results based on the results measured during my research.

1. **Changes in weight loss percentage (Δm) of stored apples depending on the storage temperature**

Based on the experimental results, I have established new linear correlations that can be used to predict the weight loss percentage (Δm) of Golden Delicious apples during storage as a function of the number of weeks elapsed (w), considering different storage temperatures (T) at the same relative humidity (RH).

D03; T=3°C; $\Delta m\ (\%) = 0.4931 \cdot w$ where $R^2 = 0.9865$; $w \in [0\text{-}12]$ weeks; RH85±5%

D15; T=15°C; $\Delta m\ (\%) = 1.5216 \cdot w$ where $R^2 = 0.9911$; $w \in [0\text{-}12]$ weeks; RH85±5%

I found that the weight loss percentage (Δm) of Golden Delicious apples during 12 weeks of storage increases linearly from the beginning of storage at both 3°C and 15°C, under constant relative humidity (RH 85 ± 5%) and in dark storage. The slope of the linear relationship is 0.4931 for apples stored at 3°C and 1.5216 for those stored at 15°C, with coefficients of determination $R^2 = 0.9865$ and $R^2 = 0.9911$, respectively.

During the statistical analysis, I used linear mixed model (LMM) and ANOVA, and the results showed a significant ($F=78.995$, $p<0.01$) difference in weight loss percentage (Δm) at different storage temperatures (D03, D15).

2. **Changes in weight loss percentage (Δm) of stored apples depending on the light and dark conditions**

Based on the experimental findings, I generated new linear equations that could be utilised for estimating the weight loss percentage (Δm) of Golden Delicious apples during storage as a function of the elapsed weeks (w), considering light (L) and dark (D) storage conditions at the same temperature (T) and the same relative humidity (RH).

L03; T=3°C; $\Delta m\ (\%) = 0.8443 \cdot w$ where $R^2 = 0.9894$; $w \in [0\text{-}12]$ weeks; RH85±5%;

D03; T=3°C; $\Delta m\ (\%) = 0.4931 \cdot w$ where $R^2 = 0.9865$; $w \in [0\text{-}12]$ weeks; RH85±5%;

I found that the weight loss percentage (Δm) of Golden Delicious apples during 12 weeks of storage increases linearly from the beginning of storage under both light and dark conditions, at a constant temperature of 3°C and relative humidity (RH 85 ± 5%). The slopes of the linear relationship are 0.8443 for apples stored in a light room storage and 0.4931 for those stored in a dark room storage, with coefficients of determination R^2=0.9894 and R^2=0.9865, respectively. During the statistical analysis, I used a linear mixed model (LMM) and ANOVA, and the results showed a significant (F=29.660, p<0.01) difference in weight loss percentage (Δm) for apples stored in light and dark rooms (D03, L03).

3. Changes in colour change (ΔE) of stored apples depending on the storage temperatures

Based on the experimental results, I developed new linear relationships that can be used to predict the change in the colour change (ΔE) value of Golden Delicious apples during storage as a function of the elapsed weeks (w), considering different storage temperatures (T) at the same relative humidity (RH).

D03; T=3℃;	ΔE = 0.5975·w	where R^2 = 0.819;	w ∈ [0-12] weeks;	RH85±5%;
D15; T=15℃;	ΔE = 1.2768·w	where R^2 = 0.8075	w ∈ [0-12] weeks;	RH85±5%;

I found that the colour change (ΔE) of Golden Delicious apples during 12 weeks of storage increases linearly at both 3 °C and 15 °C, under constant relative humidity (RH 85 ± 5%) and in a light-protected environment. For the linear models, the coefficient of determination was R^2=0.819 for apples stored at 3 °C and R^2=0.8075 for those stored at 15 °C. During the statistical analysis, I used a linear mixed model (LMM) and ANOVA, and the results showed a significant (F=130.942, p<0.01) difference in colour change (ΔE) between the two different storage temperatures (D03, D15).

4. Changes in hue angle (h°) of stored apples depending on the storage temperature

Based on the experimental results, I developed new linear relationships that can be used to predict the change in the hue angle (h°) of Golden Delicious apples during storage as a function of the elapsed weeks (w), considering different storage temperatures (T) at the same relative humidity (RH).

D03; T=3℃;	h° = -0.2913·w + 94.484	where R^2 = 0.9804;	w ∈ [0-12] weeks;	RH85±5%;
D15; T=15℃;	h° = -0.842·w + 93.356	where R^2 = 0.9784;	w ∈ [0-12] weeks;	RH85±5%;

I found that the hue angle (h°) of Golden Delicious apples changes linearly over 12 weeks of storage at both 3°C and 15°C, under constant relative humidity (RH 85 ± 5%) and in a light-protected environment. For the linear models, the coefficient of determination was R^2=0.9804 for apples stored at 3°C and R^2=0.9784 for those stored at 15°C. During the statistical analysis, I used a linear mixed model (LMM) and ANOVA, and the results showed a significant (F=28.228, $p<0.01$) difference in hue angle (h^o) between the different storage temperatures (D03, D15).

5. Changes in hue angle (h°) of stored apples depending on the light and dark conditions

Based on the experimental results, I developed new linear relationships that can be used to predict the Hue angle (h°) of Golden Delicious apples during storage as a function of the elapsed weeks (w), considering light (L) and dark (D) storage conditions at the same temperature (T=3°C) and relative humidity (RH).

L03; T=3°C; $h° = -0.3461 \cdot w + 93.582$ where $R^2 = 0.9654$; $w \in [0\text{-}12]$ weeks; RH85±5%;

D03; T=3°C; $h° = -0.2913 \cdot w + 94.484$ where $R^2 = 0.9804$; $w \in [0\text{-}12]$ weeks; RH85±5%;

I found that the hue angle (h°) of Golden Delicious apples during 12 weeks of storage changed linearly under light and dark conditions, at a constant temperature of 3°C and relative humidity (RH 85 ± 5%). For the linear models, the coefficient of determination was R^2=0.9654 for apples stored under light conditions and R^2=0.9804 for those stored in darkness.

During the statistical analysis, I used a linear mixed model (LMM) and ANOVA, and the results showed no significant (F=3.903, p=0.06) difference in hue angle (h°) between samples stored in light and dark rooms (D03, L03).

5. CONCLUSION AND SUGGESTIONS

The impact of different storage conditions on the state of Golden Delicious apples during 12 weeks was examined in this work. Non-destructive methods were used to measure weight loss percentage (Δm) and colour parameters (L*, a*, b*, hue angle, chroma, and ΔE). The research mainly focused on the effect of storage temperature and light exposure, using statistical analysis in R Studio to develop reliable predictive models.

The study investigated the effects of different storage temperatures: 3℃ (D03; RH 85±5%), 15℃ (D15; RH 85±5%), and 24℃ (D24; RH 60±5%) and the impact of storage under light (L03) and dark (D03) conditions, specifically at 3°C, on Golden Delicious apples, all maintained at constant relative humidity.

Based on the experimental results, the following conclusions can be drawn for Golden Delicious apples during storage:

- The apple weight loss percentage (Δm) increased significantly with rising storage temperatures, with the highest weight loss percentage occurring at 24℃, reaching 31.98% over 12 weeks.
- New linear correlations were developed to predict apple weight loss percentage (Δm) as a function of storage time, showing high reliability with R^2 values exceeding 0.97 for different temperature conditions.
- Statistical analysis using a linear mixed model and ANOVA confirmed significant differences ($p<0.01$) among the three temperature conditions, and post-hoc tests confirmed the effect of temperature on the apple weight loss percentage during the 12-week apple storage experiment. For D03 and D15, the weight loss percentage rate at 15°C is higher than at 3°C ($F=78.995$, $p<0.01$).
- Apples stored at 3℃ under light (L03) experienced more significant weight loss percentage (Δm) than those stored in darkness (D03), a difference supported by statistical analysis.
- The extent of colour change (ΔE) increased with temperature, with the highest rate observed in apples stored at 24℃.
- Linear relationships were established to predict ΔE values based on storage weeks, demonstrating high correlation coefficients.
- Statistical analysis confirmed significant differences in ΔE across apple storage temperatures, with post-hoc tests supporting the temperature-dependent effects.
- Apples stored under light exhibited a slightly higher rate of colour change (ΔE) compared to dark storage,

- Apple hue angle (h°) decreased with advancing storage, and higher temperatures accelerated the rate of change.
- Under constant RH (85±5%) and dark conditions, h° decreases linearly with storage time (w-weeks) at both temperatures D03 and D15, and ANOVA confirms significantly faster colour shift at 15°C than at 3°C.
- ANOVA confirmed significant differences ($p<0.01$) between apple storage temperatures, and the post-hoc test indicated that all temperature treatments significantly affected hue angle ($p<0.001$).
- No significant difference was observed in hue angle (h°) change between apples stored in light and dark.

Further studies could examine other elements influencing apple storage quality, such as certain apple varieties, ethylene production, and biochemical changes affecting texture, firmness, and sugar content.

To highlight some of the suggestions, the factors recommended for future studies include the impact of relative humidity, airflow, and packaging materials, which could help to have deeper insights into optimising storage conditions. In addition, long-term studies to examine the combined effects of temperature, light, and other environmental variables on sensory attributes such as texture and flavour are also suggested. Finally, further studies can explore integrating advanced non-destructive monitoring techniques, such as hyperspectral imaging or machine vision systems, with statistical modelling in R that could enable real-time quality tracking and predictive analysis.

6. SUMMARY

In this work, comprehensive experimental and numerical investigations were carried out to evaluate the quality of Golden Delicious apples during storage under different conditions. To achieve the aims of this research, Golden Delicious apples were obtained, grouped, and stored for 12 weeks in four storage conditions: darkroom at 3℃ (D03; RH 85±5%), darkroom at 15℃ (D15; RH 85±5%), darkroom at 24℃ (D24; RH 60±5%), and lightroom at 3℃ (L03; RH 85±5%). The experiment utilised non-destructive methods to measure weight loss percentage (Δm) and colour parameters, including L*, a*, b*, chroma (C*), hue angle (h°), and ΔE. To support the results, pH and total soluble solids (TSS) values were measured at the beginning and end of the experiment.

The research was divided into two parts: (1) First, apples were stored in a dark chamber at three different temperatures (3℃, 15℃ and 24℃) for 12 weeks to quantify temperature effects on weight loss percentage and colour parameters, and then (2) the properties of apples stored under dark D03 and light L03 conditions were examined at the same temperature. The Nix Pro wireless colour sensor and its associated application were used to measure colour parameters. All experimental investigations were conducted in the machinery and food technology laboratory at the Hungarian University of Agriculture and Life Sciences (MATE) in Gödöllő, Hungary. Statistical analyses, including ANOVA, linear mixed models and correlation analysis, were performed using R-Studio software to identify significant differences and relationships among the parameters.

The experiment outcomes revealed a significant difference ($p<0.01$) between the values measured at the start and end states for all parameters across the four storage conditions over the 12 weeks. Results showed that storage conditions, such as higher temperatures, significantly increased weight loss percentage (Δm). The D24 exhibited the highest loss, at 31.98%. Also, higher temperatures accelerated changes in colour parameters. Storing Golden Delicious apples at D03 exhibited the least colour degradation, slowed down respiration and transpiration processes, and extended shelf life. Storing apples at higher temperatures results in faster ripening, lower quality, and increased vulnerability to spoilage.

The study also revealed that weight loss percentage increased in both D03 and L03 storage conditions, with L03 causing more significant weight loss percentage. The comparison between D03 and L03 indicated that light exposure at 3℃ resulted in a slightly higher rate of colour change than dark storage, though the effect was less impactful than temperature elevation.

7. ÖSSZEFOGLALÁS (SUMMARY IN HUNGARIAN)

Ebben a munkában átfogó kísérleti és numerikus vizsgálatok kerültek elvégzésre a Golden Delicious alma minőségének különböző tárolási körülmények közötti értékelésére. A kutatás céljainak elérése érdekében a Golden Delicious almákat beszerzést követően csoportosították és 12 hétig négy tárolási körülmény között tárolták: sötétkamra 3°C-on (D03; RH 85±5%), sötétkamra 15°C-on (D15; RH 85±5%), sötétkamra 24°C-on (D24; RH 60±5%) és világoskamra 3°C-on (L03; RH85±5%). A kísérletsorozat alalmával roncsolásmentes módszerek kerültek alkalmazásra a tömegveszteség százalékos (Δm) és a színparaméterek, köztük az L*, a*, b*, a kromatikus érték (C*), a színárnyalat szöge (h°) és a ΔE mérésére. Az eredmények alátámasztására a kísérlet elején és végén megmérésre kerültek a pH-értékek és az összes oldható szárazanyag (TSS) értékei.

A kutatás két részre osztható: (1) Először az almák sötét kamrában kerültek tárolásra három különböző hőmérsékleten (3°C, 15°C és 24°C) 12 héten keresztül, hogy számszerűsíteni lehessen a hőmérséklet hatását a súlyvesztésre és a színparaméterekre, majd (2) a sötét D03 és világos L03 körülmények között tárolt almák tulajdonságai kerültek megvizsgálásra ugyanazon a hőmérsékleten, azonos párataralom mellett. A színparaméterek mérésére a Nix Pro vezeték nélküli színérzékelőt és a hozzá tartozó alkalmazást használtam. Minden vizsgálatot a Magyar Agrár- és Élettudományi Egyetem (MATE), Műszaki Intézet, Mezőgazdasági és élelmiszeripari technológiák és gépek laboratóriumában végeztem, Gödöllőn. Statisztikai elemzéseket, beleértve az ANOVA-t, a lineáris vegyes modelleket és a korrelációanalízist, az R-Studio szoftverrel végeztem a paraméterek közötti szignifikáns különbségek és kapcsolatok azonosítására.

A kísérlet eredményei szignifikáns különbséget ($p<0,01$) mutattak a kezdeti és a végállapotban mért értékek között minden paraméter esetében a négy tárolási körülmény között 12 hét alatt. Az eredmények azt mutatták, hogy a tárolási körülmények, például a magasabb hőmérséklet, szignifikánsan növelték a súlyveszteség százalékos arányát (Δm). A D24 mutatta a legnagyobb veszteséget, 31,98%-kal. Emellett a magasabb hőmérséklet felgyorsította a színparaméterek változását. A D03-as tárolású Golden Delicious alma esetében változott a legkevésbé a szín, lelassultak a légzési és párologtatási folyamatok, és meghosszabbodott az eltarthatóság. Az alma magasabb hőmérsékleten történő tárolása gyorsabb érést, alacsonyabb minőséget és fokozott romlási hajlamot eredményezett. A tanulmány azt is kimutatta, hogy a súlyveszteség százalékos aránya mind a D03, mind az L03 tárolási körülmények között nőtt, az L03 esetében jelentősebb súlyveszteség százalékos aránya volt megfigyelhető. A D03 és az L03 összehasonlítása azt mutatta, hogy a 3°C-os fénynek való kitettség valamivel nagyobb színváltozási sebességet eredményezett, mint a sötét tárolás, bár a hatás kisebb volt, mint a magasabb hőmérséklet esetén.

8. APPENDICES

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A2. Publications related to the dissertation

Refereed papers in foreign languages:

1. **Kassebi, S**., Korzenszky, P. (2024): Examination of weight loss and colour changes in Golden Delicious apples under light and dark storage conditions. *Progress in Agricultural Engineering Sciences*, Vol. 20(1), pp. 199–215. DOI: 10.1556/446.2024.00135 **(Scopus: Q2,)**
2. **Kassebi, S.**, Korzenszky, P. (2024): Influence of ambient storage on weight, color, and TSS in Golden Delicious apples: A correlational study. *Hungarian Agricultural Engineering*, Vol. 43, pp. 18–25. DOI: 10.17676/HAE.2024.43.18
3. **Kassebi, S.**, Korzenszky, P. (2024): Cold storage effects on ethylene emission, CO_2 accumulation, and TSS variation in Golden Delicious apples at 3°C. *Journal of Central European Green Innovation*, Vol. 12(3), pp. 199–215. DOI: 10.33038/jcegi.6441
4. **Kassebi, S.**, Farkas, C., Székely, L., Géczy, A., Korzenszky, P. (2023): Late shelf life saturation of Golden Delicious apple parameters: TSS, weight, and colorimetry. *Applied Sciences*, Vol. 13(1), Paper No. 159. DOI: 10.3390/app13010159 **(Scopus: Q2, IF: 2.5)**
5. **Kassebi, S.**, Korzenszky, P. (2022): The Influence of Storage Temperature on the Weight of Golden Delicious Apples. *Hungarian Agricultural Engineering*, Vol. 41, pp. 5–10. DOI: 10.17676/HAE.2022.41.5
6. Ghabour, R., **Kassebi, S**., Korzenszky, P. (2021): Simulation and experiment of apple fruits in domestic fridge. *Hungarian Agricultural Research: Environmental Management, Land Use, Biodiversity*, Vol. 30(2), pp. 11–14.
7. **Kassebi, S**., Korzenszky, P. (2021): The effect of post-harvest storage on the weight of Golden Delicious apples. *Science, Technology and Innovation*, Vol. 13(2), pp. 7–11. DOI: 10.5604/01.3001.0015.5265
8. **Kassebi, S.**, Ghabour, R., Korzenszky, P. (2021): Monitoring the preservation of apples in a domestic fridge. *Mechanical Engineering Letters: R&D: Research and Development*, Vol. 21, pp. 178–184.
9. Ben Rejeb, I., Dhen, N., **Kassebi, S.**, Gargouri, M. (2020): Quality evaluation and functional properties of reduced sugar jellies formulated from citrus fruits. *Journal of Chemistry*, Vol. 2020, pp. 1–8. https://doi.org/10.1155/2020/5476872 **(Scopus: Q2, IF: 2.8)**

Refereed papers in Hungarian:

10. Korzenszky, P. E., **Kassebi, S.** (2021): A tömegcsökkenés vizsgálata Golden Delicious alma tárolása esetén. *Acta Agronomica Óváriensis*, Vol. 62 (Ksz 1), pp. 128–139.

International conference abstracts:

11. Korzenszky, P., Farkas, A., Veres, A., **Kassebi, S**. (2024): Experimental concept to investigate the shelf life of apples for consumer storage. *Book of Abstracts*, Risk Factors of Food Chain, Nyitra, Slovakia, 2024, p. 28.
12. **Kassebi, S.**, Korzenszky, P. (2022): The impact of ambient temperature storage on the colours of Golden Delicious apples. *Book of Abstracts*, Risk Factors of Food Chain, 2022, p. 24.

13. Korzenszky, P., **Kassebi, S**. (2021): Changes in physicochemical properties of Golden Delicious apples during storage. *Book of Abstracts*, 4th International Conference on Biosystems and Food Engineering, Budapest, Hungary, 2021, Paper: E418, 1 p.

14. **Kassebi, S.**, Korzenszky, P. (2023): Effects of room temperature storage on color and weight of Golden Delicious apples. *BiosysFoodEng 2023: 5th International Conference on Biosystems and Food Engineering*, pp. E553, 1 p.
15. **Kassebi, S.**, Korzenszky, P. (2023): Impact of post-harvest cold storage on ethylene and CO_2 emissions from Golden Delicious apples. *Risk Factors of Food Chain 2023: XXIII. International Conference, September 20-22, 2023, Gyöngyös, Hungary: Book of Abstracts*, Gödöllő, Hungary: MATE Szent István Campus, 2023, p. 56.
16. **Kassebi, S**., Korzenszky, P. (2021): Effect of post-harvest storage on apple's weight. *Risk Factors of Food Chain: XXI International Conference: Book of Abstracts*, Iwonicz, Poland: Uniwersytet Rzeszowski, 2021, p. 21.

A3. Detailed results of statistical analyses

a.) Effect of storage temperature on weight loss percentage

Tukey test results for the change in percentage weight loss as a function of storage temperature.

Storage	Mean (EMMean)	SE	df	lower.CL	upper.CL
D03	2.90	0.547	32.8	1.79	4.02
D15	9.13	0.547	32.9	8.02	10.24
D24	17.03	0.550	33.5	15.91	18.15

Results are averaged throughout the week's levels. The Kenward-Roger method was applied to determine degrees of freedom. Confidence level used: 0.95

- Contrasts

Contrast	Mean Difference (Estimate)	SE	df	t-Ratio	p-Value
D03-D15	-6.23	0.774	32.8	-8.045	<0.0001
D03-D24	-14.13	0.776	33.1	-18.212	<0.0001
D15-D24	-7.90	0.776	33.2	-10.182	<0.0001

Results are averaged throughout the week's levels. Degrees of freedom method: Kenward-Roger. The p-value adjustment was performed using the Tukey method to compare a family of 3 estimates.

b.) Effect of storage temperature on calculated colour parameters (C*, ΔE, h°)

Chroma (C*)

Tukey test results for the change in chroma as a function of storage temperature.

Storage	Mean (EMMean)	SE	df	lower.CL	upper.CL
D03	53.7	0.424	32.5	52.9	54.6
D15	56.6	0.425	32.7	55.7	57.4
D24	58.2	0.429	34.0	57.3	59.0

Results are averaged throughout the week's levels. The Kenward-Roger method was applied to determine degrees of freedom. Confidence level used: 0.95

- Contrasts

Contrast	Mean Difference (Estimate)	SE	df	t-Ratio	p-Value
D03-D15	-2.82	0.600	32.6	-4.696	0.0001
D03-D24	4.42	0.603	33.3	7.329	0.0315
D15-D24	1.60	0.604	33.4	2.656	<.0001

Results are averaged throughout the week's levels. Degrees of freedom method: Kenward-Roger. The p-value adjustment was performed using the Tukey method to compare a family of 3 estimates.

ΔE

Tukey test results for the change in ΔE as a function of storage temperature.

Storage	Mean (EMMean)	SE	df	lower.CL	upper.CL
D03	3.94	0.358	32.5	3.21	4.67
D15	8.23	0.358	32.6	7.50	8.96
D24	11.61	0.363	34.2	10.87	12.35

Results are averaged throughout the week's levels. The Kenward-Roger method was applied to determine degrees of freedom. Confidence level used: 0.95

- Contrasts

Contrast	Mean Difference (Estimate)	SE	df	t-Ratio	p-Value
D03-D15	-4.30	0.506	32.5	-8.483	<.0001
D03-D24	-7.67	0.510	33.3	-15.048	<.0001
D15-D24	-3.38	0.510	33.4	-6.617	<.0001

Results are averaged throughout the week's levels. Degrees of freedom method: Kenward-Roger. The p-value adjustment was performed using the Tukey method to compare a family of 3 estimates.

Hue angle (h^0)

Tukey test results for the change in h^0 as a function of storage temperature.

Storage	Mean (EMMean)	SE	df	lower.CL	upper.CL
D03	92.7	0.543	32.8	91.6	93.8
D15	88.2	0.5433	32.9	87.1	89.3
D24	85.1	0.545	33.3	84.0	86.2

Results are averaged throughout the week's levels. The Kenward-Roger method was applied to determine degrees of freedom. Confidence level used: 0.95

- Contrasts

Contrast	Mean Difference (Estimate)	SE	df	t-Ratio	p-Value
D03-D15	4.52	0.768	32.9	5.890	<0.0001
D03-D24	7.64	0.769	33.1	9.935	<0.0001
D15-D24	3.12	0.769	33.1	4.054	0.0008

Results are averaged throughout the week's levels. Degrees of freedom method: Kenward-Roger. The p-value adjustment was performed using the Tukey method to compare a family of 3 estimates.

A4. R-studio script

```
library(readxl)
library(dplyr)
library(ggplot2)
#library(extrafont)
#font_import()
#loadfonts(device = "win")
library(svglite)
library(lme4)
library(stats)
library(tidyr)
library(rstatix)
library(emmeans)
library(afex)
library(ez)
library(latex2exp)

# Load the dataset from the Excel file
file_path <- "alma_salma.xlsx"
apple_data <- read_excel(file_path)

# Display the structure and first few rows of the dataset
str(apple_data)
head(apple_data)

# Ensure factors are correctly formatted
apple_data$Storage <- as.factor(apple_data$Storage)
apple_data$Week <- as.factor(apple_data$Week)
apple_data$ID <- as.factor(apple_data$ID)

# Basic descriptive statistics
summary(apple_data)

analysis_data <- apple_data[
  #apple_data$Storage=="L03"
  # apple_data$Storage=="L03" | apple_data$Storage=="D03"
  #apple_data$Storage=="D03" | apple_data$Storage=="D15" | apple_data$Storage=="D24"
  apple_data$Storage=="D03" | apple_data$Storage=="D15"
  ,]

 analysis_data <- analysis_data[
  analysis_data$Week!=13,]

#-------------------------
#-------------------------
#-------------------------
# Linear model
model <- lmer(Hue_angle ~ Week * Storage + (1 | ID), data = analysis_data)
summary(model)

anova(model)

# pairwise comparisons (Tukey)
emmeans_results <- emmeans(model, pairwise ~ Storage | Week, adjust = "tukey")
summary(emmeans_results)
```

```
# Plot
emm_df <- as.data.frame(emmeans_results$emmeans)
emm_df

ggplot(emm_df, aes(x = Week, y = emmean, group = Storage)) +
  geom_line(size = 0.5) +
  geom_point(size = 1) +
  geom_errorbar(aes(ymin = lower.CL, ymax = upper.CL), width = 0.2) +
  labs(title = "Estimated Marginal Means of Weight Loss Percentage Across Weeks",
       x = "Week",
       y = "Estimated Mean Weight Loss percentage",
       color = "Storage Condition") +
  theme_minimal() +
  theme(plot.title = element_text(hjust = 0.5))

myplot <- ggplot(emm_df, aes(x = Week, y = emmean, color = Storage, group = Storage)) +
  geom_line(color = "gray", linewidth = 0.8) +
  # geom_smooth(method = "lm", aes(group = Storage), linewidth = 1.5,se = FALSE) +
  geom_point(size = 2) +
  geom_ribbon(aes(ymin = lower.CL, ymax = upper.CL), fill = "lightblue", alpha = 0.2) +
  geom_jitter(data = analysis_data, aes(x = Week, y = Weight_loss, fill=Storage),
              width = 0.2, height = 0, alpha = 0.2, ) +
  scale_color_manual(values = c("D15" = "#F1C40F", "D03" = "#66A85D", "D24" = "#D94F5F", "L03" =
"#3498DB")) +
  # labs(title = "Estimated Marginal Means of Weight Loss Percentage  Over Weeks with Raw Data",
  #      x = "Storage periods [w]", y = "Chroma [-]") +
  # labs(title = "Estimated Marginal Means of Weight Loss Percentage Over Weeks with Raw Data",
  #      x = "Storage periods [w]", y = TeX("\\textrm{hue angle}\\ [\\circ]")) +
  labs(title = "Estimated Marginal Means of Weight Loss Percentage Over Weeks with Raw Data",
       x = "Storage periods [w]", y = TeX("$\\Delta m\\ [\\%]")) +
  theme_minimal()

myplot

# Export to SVG
ggsave("figure_4_1.svg", plot = myplot, width = 8, height = 6, dpi = 300)

ggsave(myplot, device = png, filename = "figure_4_1.png", bg = "transparent", width=8, height=6,
dpi=300)

# cairo_pdf("figure_4_4.pdf", bg = "transparent", width = 8, height = 6)
# myplot
# dev.off()

lm_emm_df <- emm_df[emm_df$Storage=="L03",]
lm_emm_df$Week <- as.numeric(lm_emm_df$Week)

model <- lm(emmean ~ Week, data = lm_emm_df)
summary(model
```

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Salma Kassebi