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STUDY OF APPLE FRUIT RESPIRATION UNDER SPECIAL CONDITIONS

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1.0 INTRODUCTION

1.1 Background of Study

Fruits are identified as one of the most important diets for human development due to their essential nutrients, such as vital minerals, complex carbohydrates, dietary fibre, and more (de Andrade et al., 2017). Frequent consumption of fresh fruits helps to improve physical and mental health and is also associated with reducing the risk of cancer, neurological diseases, cardiovascular diseases, and other chronic diseases (Turati et al., 2015). Apples have been researched widely due to their abundance of nutrients and the presence of various bioactive compounds like phytochemicals, pectin, dietary fibres, and vitamin C (Vallée Marcotte et al., 2022). In Hungary, apples are one of the most consumed fruits (Medve, 2023) and apple is recommended to be consumed fresh in order to retain their nutritional and health benefits (Wang et al., 2022). However, the purchasing decision of apple fruits is predominantly influenced by their external characteristics which are the size, colour, shape, and freshness of the apples (Meike et al., 2022). In recent times, consumers have become much more concerned about eating natural foods with a specific concentration on the qualities of fruits like flavour, colour, structure, etc. (Mesías et al., 2021). Nevertheless, the nutrients, which are hidden attributes, also contribute to the purchasing decision of apples, and researchers have shown that postharvest life greatly impacts the appearance, flavour, and nutritional qualities of fresh apples (Valenzuela, 2023).

Apple fruits are an integral component of the global agriculture system because they are subject to intricate physiological postharvest conditions, with respiration being an important indicator of their metabolic activities (Saletnik et al., 2022a). Among the diverse array of fruits, apples stand out not only for their economic significance but also as a model organism for understanding postharvest methods(Mushtaq, 2022; Thapa et al., 2024). However, they are perishable products with a high metabolic and respiration rate, resulting in a limited shelf life (Saletnik et al., 2022a). Enhancing postharvest treatment for fresh products is crucial for increasing food availability, as losses during postharvest handling can reach 25- 28% (H. Wang et al., 2022). As apples are taken into storage conditions, a critical phase in their journey from the farms to consumers, the modulation of respiration rates becomes a pivotal determinant of their qualities, shelf life, and market or price determination (Liu et al., 2022). However, the postharvest period, marked by intricate biochemical transformation, influences the texture, flavour, and nutritional content of this fruit (Mushtaq, 2022).

1.2 Significance of Study

Respiration, a central metabolic process in this context (Ghosh & Dash, 2020), is indicative of the overall metabolic vigour of Apple fruits during storage (Weber et al., 2020). It encompasses the uptake of oxygen and release of carbon dioxide, reflecting the balance between catabolic and anabolic processes within the fruit's tissues (Ghosh & Dash, 2020). The modulation of respiration rates under varying storage conditions emerges as a critical aspect to be considered because it holds the key to preserving the qualities of apples and extending their market availability. The investigation of apple respiration rate is a critical area of study that holds significant implications for postharvest handling and preservation. Once apples are harvested, they remain living biological entities with ongoing metabolic activity (Hadish, 2023). Deprived of their supply of water, photosynthates, and minerals from the tree, they are now relying on their stored reserves of water and carbohydrates (Mushtaq, 2022). From the point of harvest to consumption, apples undergo a series of biochemical transformations. While some of these changes enhance their palatability, such as flavour development, starch to sugar conversion, and decreased organic acid levels (Doerflinger et al., 2015; Musacchi & Serra, 2018) others, notable transpiration, and respiration, contribute to inevitable postharvest losses (Rahman, 2020). Notably, the respiration rate of apples is influenced by storage conditions, such as temperature, oxygen, and carbon dioxide levels. Some research has shown that the main rate of respiration varies directly with temperature, with a significant increase in CO_2 and output and oxygen uptake as temperature rises (Wang et al., 2022).

Understanding the changes that occur in apples due to their respiration rate is essential for optimizing their nutritious values, and storage conditions, extending shelf life, and mitigating postharvest losses. The findings of this research will contribute to scientific knowledge and practice by providing insights into the postharvest physiology of apple fruits as well as the metabolic processes that occur within the fruit which have implications for their nutritional quality and flavour development. Furthermore, these findings will inform agricultural practices by helping farmers optimize the growing and storage conditions of apple fruits in order to enhance their quality and shelf life.

2.0 GOAL OF THE THESIS

2.1 Problem Statement

Postharvest storage of fruits is a critical stage in the food supply chain because the impact of various storage conditions and the respiration rate of fruits is a key area that is essential to the effectiveness of the supply chain (Wang et al., 2020). Several studies have reported that respiration, the process by which apples take in oxygen and release carbon dioxide, directly influences the fruits' physiological state, shelf life, and overall qualities (Nicuţă et al., 2021; Thewes et al., 2022; Weber et al., 2020). Higher respiration rates lead to the rapid consumption of carbohydrates, resulting in quicker deterioration which will lead to a decrease in the quality of the apple fruits and shorten its shelf life (Brizzolara et al., 2020; Saletnik et al., 2022). Therefore, it is crucial for farmers or apple traders to understand the fundamentals of the scientific principles underlying the physiological processes of apples in order to formulate conditions more suitable for their commodities, minimize loss, and decrease food waste in other to promote sustainable development goals.

2.2 Aim of Thesis

The essential aim of this thesis is to evaluate the respiration, potential gas changes measurement, and test methods in the control of the atmospheric contents of fresh-cut 'Idared' apple fruits during postharvest storage. The values, strategies, and tools derived from the findings and observations will contribute to the fulfillment of the purpose of the work which is to equip farmers and apple traders with a profound understanding of the specific principles underlying the physiological process of fresh-cut apples during postharvest storage. By unraveling this principle, it will empower stockholders to formulate storage conditions that are not only tailored to the unique needs of their apple commodities but also effective in minimizing loss. The overarching goal is to contribute significantly to the reduction of food waste within the supply chain, aligning with broader sustainable development objectives. In essence, the evaluation of the respiration of fresh-cut apples within the context of postharvest storage emerges as a vital subject for exploration. This research holds the potential to revolutionize storage practices, thereby fostering a more sustainable and resilient food supply chain.

2.2.1 Objectives of Thesis

The specific objectives of this thesis are to:

1. Evaluate the respiration rates of fresh-cut apple fruits under varying atmospheric conditions during postharvest storage.
2. Measure potential gas changes, including oxygen and levels, to assess their impact on the quality and shelf life of fresh-cut apple fruits.
3. Compare and analyze different testing methods for monitoring atmospheric contents in postharvest storage environments for fresh-cut apples.

3.0 LITERATURE REVIEW

3.1 Introduction

Rising consumer preferences or demand for nutritious fruits have prompted a reasonable concern in the fruit production industries (Mesías et al., 2021). This shift has necessitated the development of cost-effective and sustainable techniques to prolong the shelf life of fruits, posing various challenges for fruit production sectors (Sridhar et al., 2021; Yadav et al., 2022). Among these challenges, the technologies used, such as controlled atmospheric storage and packaging, emerge as prevalent strategies to extend the freshness of fruits (Hayat et al., 2024). Moreover, in the last decades, the emergency for nutritious fruit processing techniques has gained prominence in global fruit production circles. These innovative methods prioritize not only the preservation and extension of shelf life but also the retention of nutritional integrity and enhancement of functional attributes in the production sector (Kumar et al., 2023; Olunusi et al., 2024; Pravallika & Chakraborty, 2022).

Therefore, the evaluation of the respiration of apple fruits in different conditions is a critical area of research in postharvest physiology and storage management. This literature review aims to assess and comprehend the dynamics of respiration in fresh-cut apples, shedding light on how the respiration process occurred. The significance of this study extends beyond mere academic curiosity, as it directly informs the development of strategies for optimal postharvest handling and storage practices, with implications for enhancing fruit qualities, extending shelf life, and minimizing postharvest losses. Through a comprehensive exploration of the physiology, postharvest technology, storage conditions, and respiration rates exhibited by apple fruits across diverse environmental parameters, this literature review aims to provide a comprehensive overview of the available findings conducted on the respiration of apple fruits in various conditions, including the impact of temperature, oxygen, and carbon dioxide levels on respiration rate.

3.2 The Apple Fruit: An Overview

The apple is scientifically known as *Malus domestica*, and it is a highly valuable fruit that holds significant economic significance, especially in temperate countries (Mushtaq, 2022; Patocka et al., 2020). It is extensively cultivated and highly valued by both farmers and consumers. The fruit's popularity arises from its capacity to thrive in many ecological situations and its significant nutritional content (Szot et al., 2022). Numerous studies have emphasized the high nutritional value of apples, solidifying their claim as a popular choice for health-conscious customers (Antonic et al., 2020; Bondonno et al., 2017; Koutsos et al., 2015; Patocka et al., 2020; Pazzini et al., 2021). According to the data from Statista, Food and Agriculture Organization (FAO), and the United States Department of Agriculture (USDA), apples accounted 93.14 million tons, 95.84 million tons, and 82.9 million tons of the global fruit production in 2021, 2022, and 2023 respectively, ranking third only to bananas and watermelon (FAOSTAT, 2023; Shahbandeh, 2024b; USDA, 2023), highlighting its significant role in the world's food provision.

Apples can be classified into red and non-colored types, and they are differentiated not only by their physical characteristics but also by how consumers perceive their ripeness and flavor (Musacchi & Serra, 2018; USDA, 2023). Red apple cultivars like 'Red Delicious', 'Fuji', and 'Royal Gala' are commonly linked to high marketability and economic value because consumers favor them (Cliff & Toivonen, 2017; Colavita et al., 2021; Dar et al., 2019). As a result, apple breeders and researchers have dedicated significant attention to the development of fruit color to meet market requirements and improve the commercial viability of apple varieties (Chen et al., 2021).

Apples have a widespread economic influence (O'Rourke, 2021) with Europe being a major producer accounting for 14.7% of global apple production in 2023 (Shahbandeh, 2024a). Apple cultivation covers an area of about five million hectares globally (Shah et al., 2022), with Europe alone generating around 12.2 million metric tons in 2023 (Shahbandeh, 2024a). Apples are prized by customers for their nutritional composition, which includes vital elements such as sugars, organic acids, vitamins, fibers, and antioxidants (Vidović et al., 2020). However, differences in these compounds can arise due to factors like climate, cultivar type, orchard management strategies, and postharvest treatment (Musacchi & Serra, 2018).

Significantly, postharvest storage is an important part of apple preservation as apples are generally held for many months to a year under controlled atmosphere conditions (Mushtaq, 2022; Radenkovs & Juhnevica-Radenkova, 2018). This storage approach is critical for maintaining fruit quality and safety; however, it leads to issues connected to postharvest pathogen management as highlighted by research studies (Argenta et al., 2021). Therefore, understanding the temporal changes in microbial populations during storage is critical for preventing postharvest infections and lowering losses along the supply chain.

3.2.1 Health Benefit of Apples

From a health viewpoint, apples have been labeled a "healthy food option" due to their rich nutritional composition and phytochemical richness (Jideani et al., 2021). They are cholesterol-free and include different bioactive components such as flavonols, anthocyanins, quercetin, and dietary fibers like pectin (Hussain et al., 2021). Research has shown that consuming apples is connected with several health advantages, including antioxidant effects, cholesterol-lowering, diabetes prevention, and increased overall well-being (Bator et al., 2024; Bondonno et al., 2017; Hussain et al., 2021; Koutsos & Lovegrove, 2015; Pazzini et al., 2021). Additionally, apples are a versatile fruit consumed in numerous forms, including whole fruits, juices, pomace, and cider, each giving unique health advantages (Fernandes et al., 2022; Kauser et al., 2024). However, research continues to evaluate whether different apple forms produce equivalent health advantages, with some studies suggesting that whole apples may have greater nutrient density compared to processed forms like juice (Niklas et al., 2015). Despite these arguments, the widespread use of apples and their derivatives shows their relevance as a valuable source of nutrition and well-being.

Below are some of the notable health benefits of unprocessed and fresh apples as highlighted in the literature above:

1. **Lower Risks of Chronic Diseases:** Apples are linked to a lower chance of developing chronic conditions, including diabetes, heart disease, and cancer.
2. **Improved Weight Loss:** Since apples are high in fibre and water, they have been reported to induce a sense of making being filled when eaten and as such, are good food choices for weight loss.
3. **Improved Cardiovascular Health:** Apples have been linked to a lower chance of heart disease, lower cholesterol, and lower risk of blood pressure complications.
4. I**mproved Digestive Health:** Apples are a good source of fibre which can aid digestion and help with diarrhoea and constipation.
5. **Improved Brain Health:** Research has shown that apples can help with brain health, easing symptoms of Alzheimer disease and age-related memory loss.

3.3 Cultivars of Apple

Different studies have carried out research based on a wide range of differences in quality characteristics of different apple varieties (Contessa & Botta, 2016; Musacchi & Serra, 2018). The overall quality of apples during postharvest storage is determined in part by internal and external factors including acid content, soluble solids/total acid ratio, firmness, maturity index, starch degradation index, and soluble solid concentration (Banoo et al., 2018; Mushtaq, 2022; Radenkovs & Juhnevica-Radenkova, 2018). Also, external indicators of apple quality include fruit size, shape, and weight as highlighted by studies (Musacchi & Serra, 2018). These characteristics affect the fruit's shelf life and market appeal in addition to reflecting the fruit's maturity and taste preferences. The quantity and makeup of polyphenolic chemicals in apples have also received attention because of their advantageous bioactivities (Jakobek et al., 2020; Starowicz et al., 2020), which makes evaluating apple varieties even more complex.

Apple cultivars that are commercially popular like ‘Fuji’, ‘Golden Delicious’, and ‘Gala’ are highly regarded by customers due to their firmness, crunchiness, and sweetness (Colavita et al., 2021; Idun, 2016; Kim, 2020). The world of apple variations, however, goes beyond these popular cultivars to include ancient and native cultivars that are sometimes disregarded but have been reported by studies to be important due to their visual appeal, distinctive flavor profiles, high nutritional value, and resistance to environmental stresses (Szot et al., 2022). Older cultivars have demonstrated potential qualities like higher levels of polyphenol and improved tolerance for those with apple intolerance, even though they have been examined less than commercial varieties in terms of quality indices and polyphenol content (Duralija et al., 2021; Kschonsek et al., 2019). This highlights how crucial it is to protect and research these lesser-known cultivars due to their possible health advantages and attractiveness to consumers.

Apple varieties are diverse in both their breeding histories and their places of origin. Studies show their unique qualities such as taste, texture, color, and adaptability for various culinary applications (Hussain et al., 2021; Idun, 2016; Jakobek et al., 2020). A few examples of the diverse range of alternative varieties offered to consumers and agricultural stakeholders are the following: 'Red Delicious, 'Granny Smith, 'Cortland, 'Fuji, 'Gala, 'Golden Delicious, 'Ginger Gold, 'Honeycrisp, 'Jonathan, 'Jonagold,' 'Rome Beauty,' and 'McIntosh' (Horbach, 2023; Leighty’s, 2024).

Furthermore, the features of apple cultivars are shaped by environmental and geographical factors such as variations in the polyphenol content, sweetness levels, nutritional content, visual appearance, and flavor profile are noted depending on the growth conditions (Grabska et al., 2023; Kschonsek et al., 2019). The comparison of conventional and organic farming methods, the amount of crop grown on apple trees and even the location of the apple orchard can affect the polyphenol content and qualitative characteristics of the fruit as highlighted by studies (Jakobek et al., 2020; Średnicka-Tober et al., 2020). It is therefore crucial for consumers looking for a variety of apple selections as well as producers trying to maximize growing methods for desired fruit qualities to comprehend these distinct factors.

Figure 1. Different Apple Cultivars (Lončarić et al., 2023)

3.3.1 *Malus domestica* Borhk. cv. Idared

'Idared' (*Malus domestica* Borkh) is an apple cultivar that is known for being juicy and well-colored. It has gained popularity among customers because of its mildly tart yet pleasant flavor and superior preservation capabilities (Kim et al., 1993; Skendrović Babojelić et al., 2007). 'Idared' is a cross between Jonathan and Wagener apples and is indigenous to the United States. They have a lengthy history that began with research and development at the University of Idaho in the 1930s (Hanson, 2005). They have been grown throughout the world's apple-growing regions and in North American markets, where they have become well-known for their exceptional attributes as a cultivar for home gardens (Fisher & Kitson, 1991). 'Idared' apples can be consumed in the late fall and winter months, with their peak flavor development usually taking place around January. Its use season is from November to March (Specialty Produce, 2024).

Their shape is round to slightly flattened, and they range in size from medium to giant. The apples' striking and appealing hue is displayed by their yellow-green foundation that is topped with a vivid to dark crimson blush with noticeable streaking (Hanson, 2005; Specialty Produce, 2024). 'Idared' apples have firm, fine-grained, watery flesh that is pale yellow to ivory in color and occasionally has a pink tint. This flesh has a crisp and crunchy feel. The apples' distinctive form is completed by a small center core that contains tiny black-brown seeds (Green, 2004).

In terms of nutritional quality, ‘Idared’ apples are a good source of several important minerals, such as fiber, potassium, vitamin K, calcium, manganese, zinc, copper, phosphorus, magnesium, and vitamin E. The skin's rich red hue is a result of the anthocyanins that give it its antioxidant qualities and shield cells from oxidative damage (Hanson, 2005; Skendrović Babojelić et al., 2007; Specialty Produce, 2024).

Figure 2. ‘Idared’ Apple (Hebofrut, 2023)

3.4 Apple Production in Hungary

In Hungary, the cultivation of apples holds considerable significance, with extensive apple orchards occupying a substantial portion of agricultural land and apple sales occupying a substantial market size in the food sector. (Arthey & Ashurst, 2012; Kowalska et al., 2022). Apples represent the foremost fruits in Hungary, recording about 500 thousand tons in production for the year 2023; this number is double what was produced in 2022 as reported by credible news media (Nieuwsbericht, 2023). Among the varieties cultivated in Hungary are both traditional and historic types. Historic types found in Hungary include *Malus domestica* Borkh .cv. ‘Idared’ apples, are renowned for their historical significance, self-fertility, and resilience (Ebadi et al., 2022; Surányi, 2014). Furthermore, the traditional orchards in Hungary harbours indigenous varieties such as Sovari and Batul apples, which were prevalent until the late 19th century (European Specialist in Traditional Orchards, 2023). However, it is worth noting that traditional orchards have faced diminished economic viability due to modernized fruit cultivation practices which have incorporated new varieties and technologies (Takács-György et al., 2018).

Notably, the apple industry and apple farmers in Hungary have been facing some challenges in recent years due to issues with the selection of apples varieties which has necessitated an expansion on the range of varieties tailored to contemporary demands (Király et al., 2015). To mitigate this challenge, several reports have stated that modernizing technologies frameworks and embracing innovation are imperative (Jin et al., 2022; Z. Wang et al., 2021).

3.5 Postharvest Physiology of Apples

After harvesting, apples undergo a variety of physiological and structural changes that are part of the intricate process known as postharvest physiology (Wang et al., 2023). Several changes, such as fruit softening, respiration, starch hydrolysis, chlorophyll degradation, and membrane modifications, are indicative of fruit ripening (Gundewadi et al., 2018a; Pareek, 2016). The quality and shelf life of apples may be greatly impacted by these modifications. A key strategy for reducing these postharvest alterations is controlled atmosphere (CA) storage, which involves keeping carbon dioxide concentrations higher and oxygen levels lower to inhibit biological reactions (Cukrov et al., 2019; Yahia et al., 2019a). Numerous important factors, such as firmness, color, Total Soluble Solids (TSS), sugar content, and titratable acidity, impact the quality of apples. Texture and firmness are related, and flavor characteristics are influenced by TSS, sugar, and acidity (Musacchi & Serra, 2018; Mushtaq, 2022). These factors are necessary and can impact market acceptability and customer satisfaction.

Studies have shown that the firmness of apples is lost due to cell wall alterations caused by enzymatic activity like β-galactosidases, α-L arabinofuranosidases, polygalacturonase, pectate lyase, methylesterases, and β-galactosidases during ripening (Dheilly et al., 2016; Gwanpua et al., 2016; Yang et al., 2018). Additionally, apple color development is linked to ripening and involves the breakdown of other pigments, including chlorophyll, which is regulated by temperature and light energy (Gundewadi et al., 2018b; Musacchi & Serra, 2018; Solovchenko et al., 2019). Also, the flavor is mostly dependent on the ratio of sugar to acidity, and variations in the titratable acid concentration during storage can impact fruit flavor (Pott et al., 2020). Furthermore, the apple's sweetness is affected by the soluble solid content, which includes sugars, inorganic salts, and organic acids, and may change according to the season, postharvest handling, cultivar, and chemical treatment (Shewa et al., 2022; Watkins, 2017).

Apple postharvest losses are a major problem and they arise because of several variables, including handling bruises, harvesting apples before they are fully mature, harvesting methods, harvesting conditions, and postharvest infections (Argenta et al., 2021; Springael et al., 2018). Studies have shown that apples that are stored in a controlled atmosphere are more resistant to atmospheric disorders such as damage from high carbon dioxide or low oxygen levels (Büchele et al., 2023a; Kawhena et al., 2021), but in order to avoid unwanted consequences like internal browning or alcoholic flavor, research recommends that gas levels must be optimized (Yahia et al., 2019b)

Significantly, the postharvest physiological problems of apples, such as skin cracking and browning, are impacted by environmental factors and genotype (Sidhu et al., 2023). Enzymatic browning processes involve phenolic chemicals such as dihydrochalcones, flavonoids, anthocyanins, and hydroxycinnamic acids. Browning reactions involve enzymes like polyphenol oxidase (PPO) and peroxidase (POD), and the degree of browning is determined by the activity of these enzymes, which differs between cultivars as highlighted by several study findings (Arnold & Gramza-Michałowska, 2022; Serra et al., 2021). It is worth noting that improved sanitation and storage methods are part of the fight to prevent postharvest losses and preserve the fruit's quality (Faqeerzada et al., 2018; Porat et al., 2018), but there may still be obstacles in accurately identifying and preventing physiological problems. To reduce losses and improve apple postharvest management, it is essential to comprehend the relationships that exist between phenolic compounds, enzymatic activity, cultivars, and environmental conditions.

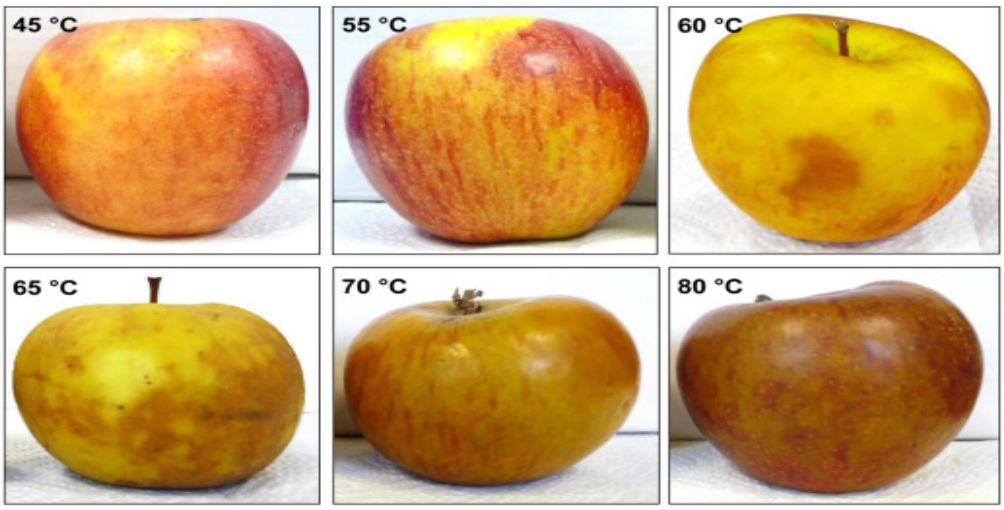

Figure 3. Effect of Temperature on Stored Apples (Kabelitz & Hassenberg, 2018)

3.5.1 Physiology of Fresh-Cut Apples

The complex mechanisms underlying the physiology of fresh-cut apples are influenced by microbial activity, textural alterations, and enzymatic browning (Shrestha et al., 2020). Apples inevitably lose some of their tissue during minimum processing, which increases their vulnerability to deterioration and shortens their shelf life (Liu et al., 2019). In the physiology of fresh-cut apple, enzymatic browning is influenced by changes in polyphenol oxidase (PPO) activity and phenolic substances (Fan, 2023) while microbial growth is accelerated by enzyme release and substrate mixing (Shrestha et al., 2020). Softening is another problem that is brought on by metabolic problems and ethylene production (R. Soliva-Fortuny & Martín-Belloso, 2020a). Promising innovations to postpone quality decline include calcium dipping (Giacalone & Chiabrando, 2018), 1-MCP therapies (Hu et al., 2020), and modified atmosphere (MA) storage (Cortellino et al., 2015). Therefore, in order to preserve the flavor, texture, aesthetic appeal, and shelf life of fresh-cut as well as their marketability, it is imperative that physiological challenges be taken care of.

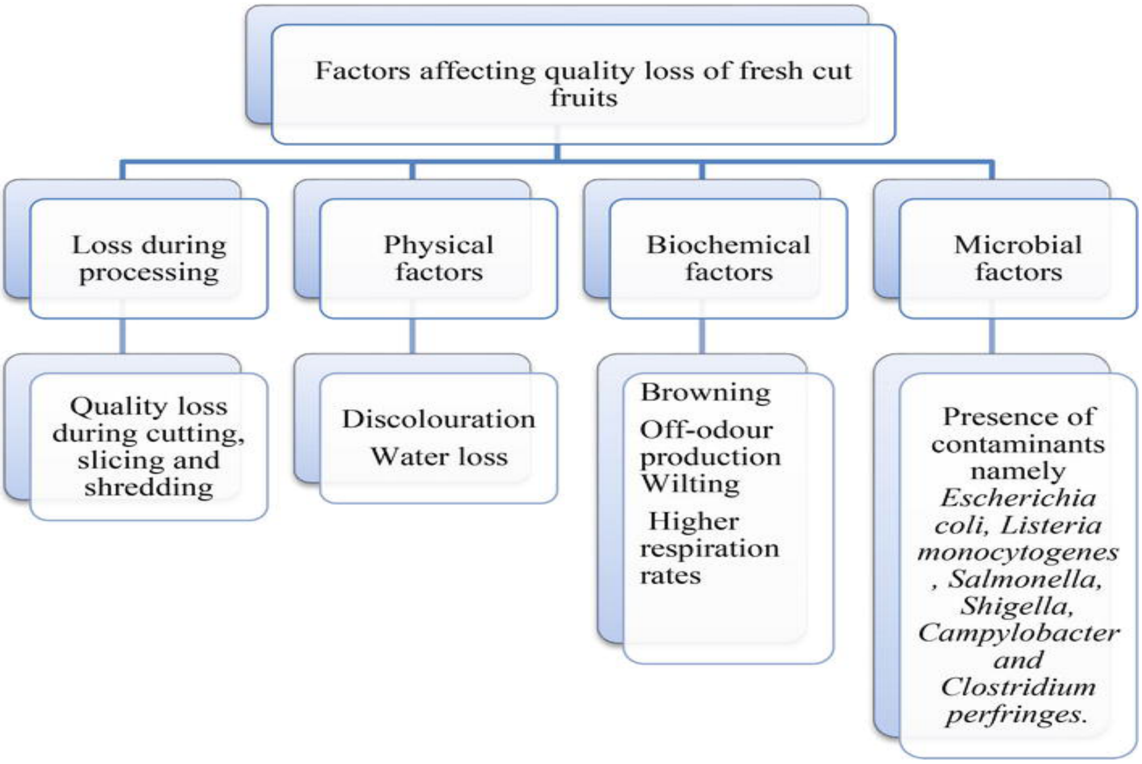

Figure 4. Factors Affecting Quality of Fresh-Cut Fruits (Nikhanj et al., 2022)

3.6 Respiration in Apple Fruits

Temperature plays a crucial role in regulating the respiration rate of fruits and vegetables, including apples (Gundewadi et al., 2018b; Ho et al., 2018). Several researchers have emphasized the impact of temperature and atmospheric composition on fruit respiration and transpiration (Ghosh & Dash, 2020; Ho et al., 2018; Jalali et al., 2020; Nicuţă et al., 2021; Thewes et al., 2022). Temperature is identified as the primary external factor influencing respiration, with biological reactions increasing significantly with rising temperatures (Bal, 2018; Saltveit, 2019). However, extremes in temperature can lead to enzymatic denaturation or physiological injuries as highlighted by study findings, affecting respiration rates and overall fruit quality (El-Ramady et al., 2015; Sharma, 2020). Therefore, it is safe to say that, controlling temperature and designing effective storage systems is crucial for prolonging the shelflife of fruits.

Respiration in apples is a metabolic process that provides energy for biochemical activities (Saltveit, 2019). A study highlighted that aerobic respiration involves the breakdown of organic reserves into simpler molecules like carbon dioxide and water, releasing energy (Gundewadi et al., 2018b). This ongoing metabolic process continues after harvest as posited by study findings, thereby contributing to the reduction in shelf life (Cortellino et al., 2015; Shewa et al., 2022). However, respiration rates are directly proportional to storage temperature according to studies which allows for increased shelf life at lower temperatures (Giuggioli et al., 2015; Massaroni et al., 2019).

Studies exploring innovative methods to enhance apple quality post-storage have emerged. A study investigated the use of low magnetic fields to improve apple quality during storage. Results indicated that treated apples exhibited higher quality metrics, including total soluble solids and titratable acidity, along with extended shelf life and reduced respiration rates (Saletnik et al., 2022b). Similarly, another study examined mitochondrial activity and enzyme changes during the climacteric phase of fruits, shedding light on metabolic shifts influencing respiration rates during storage (Silva et al., 2024).

Mathematical modeling and kinetic studies have also contributed significantly to understanding apple respiration dynamics. A study utilized enzyme kinetics models to predict respiration rates at different temperatures and the study findings emphasized the role of oxygen and carbon dioxide concentrations in regulating the respiration rates of stored apples (Mangaraj & Goswami, 2008). Similarly, another study developed a kinetic model correlating respiration rates with oxygen partial pressure, crucial for controlled atmosphere storage and the findings indicated that the enzymatic oxidations of the apples were directly related to the respiratory substrate (Andrich et al., 1991).

Advancements in storage technologies, such as dynamic controlled atmosphere (DCA), have shown promise in preserving apple quality. Two studies evaluated the quality of 'Royal Gala' apples and Braeburn apples respectively using DCA, the study findings noted lower ethylene production and respiration rates compared to static controlled atmosphere (CA) storage (Weber et al., 2015, 2020). These studies further highlight the importance of temperature and atmosphere control in maintaining fruit quality during long-term storage.

Furthermore, studies have explored the relationship between storage disorders and biochemical changes in apples with emphasis on factors like respiration rate. A study investigated storage disorders like bitter pit and cork spot in 'Royal Delicious' apples and the findings of this study linked calcium ion content, ethylene evolution, and respiration rates to disorder occurrence (Kumar et al., 2018). Similarly, another study reviewed the relationship between oxygen level, fermentation, respiration, and fruit quality retention in stored apples; the study's findings revealed that lower oxygen levels during storage led to slower respiration, slower metabolism and senescence, and reduced ethylene biosynthesis (Wright et al., 2015). Understanding these correlations can aid in developing strategies to mitigate storage-related issues and improve the postharvest quality of apples.

Overall, the reviewed literature on apple respiration highlights the important relationship between temperature, atmosphere, metabolic processes, and storage conditions. It also shows that advancements in modeling, storage technologies, and biochemical studies may offer valuable insights for farmers and other stakeholders to optimize postharvest practices and enhance apple quality and shelf life.

3.7 Influence of Temperature on Apple Respiration

Research studies have consistently underscored the impact of temperature fluctuations on the respiration rate of apple fruits, elucidating a pivotal facet in the domain of postharvest physiology (Andrich et al., 1998; Dandekar et al., 2004; Mangaraj & Goswami, 2008). The application of the Arrhenius equation, rooted in the principles of enzyme kinetics, has been used in numerous studies to present a sophisticated and scientifically grounded methodology for prognosticating the respiration rates of apple fruits about both oxygen levels and temperature (Dandekar et al., 2004; Johnston et al., 2001; Karacabey & Buzrul, 2017; Mangaraj et al., 2023; Mangaraj & Goswami, 2008). The utilization of the Arrhenius equation offers a systematic and mechanistic approach (Ghosh & Dash, 2020), providing a theoretical framework to elucidate the complex relationship between the respiration dynamics of apple fruits and the prevailing environmental conditions. When considering the relationship between enzymatic reactions, temperature, and oxygen concentration, this approach enables a more comprehensive understanding of the underlying biochemical processes governing respiration.

Empirical findings within this study reveal a compelling correlation wherein the mean respiration rate of apple fruits exhibits a proportional variation with temperature. Notably, an escalation in temperature is concomitant with a discernible increase in both carbon dioxide output and oxygen uptake. This empirical observation sheds light on the thermodynamic nature of respiratory activity in apple fruits, demonstrating the heightened metabolic rates and intensified gas exchange associated with elevated temperature (Dandekar et al., 2004; Johnston et al., 2001; Karacabey & Buzrul, 2017; Mangaraj et al., 2023; Mangaraj & Goswami, 2008).

In response to those findings, the implementation of an applicable storage strategy emerges as a consensus within the realm of postharvest management. The deliberate reduction of storage temperatures emerges as a widely adopted practice, strategically employed to curtail the respiration rate of apple fruits (Büchele et al., 2023a; Shakeel et al., 2022). This judicious intervention aligns with the established scientific correlation, aiming to harness the inherent thermodynamic principles that dictate respiration activity. By modelling storage conditions, particularly through lowering temperatures, this practice serves as an effective means to mitigate metabolic processes, thereby extending the shelf life of apple fruits.

3.8 Influence of Storage Duration and Conditions on Apple Respiration

Recently, consumers are now more interested in highly nutritious fruits that support health enhancement and this interest has been growing rapidly. Different researchers have shown that apples have occupied an important position in the chain of the human diet and up to date have remained among the most widely consumed fruits in the world (Butkeviciute et al., 2022). The nutritional properties and the uniqueness of the fruit of the apple to the consumer are determined by lot of factors including storage duration and storage conditions (Mushtaq, 2022; Shakeel et al., 2022; Watkins, 2017). The storage duration and conditions of apples can also significantly affect their respiration rate and quality attributes as highlighted by study findings (Saletnik et al., 2022c; Thewes et al., 2021).

Some postharvest management practices like controlled atmospheric storage (CA) can slow down the respiration rate of the fruit by regulating the concentration of Oxygen (O_2) and

Carbon-dioxide (CO_2) in the environment used to store them, thereby maintaining the apple's physical and nutritional qualities (Büchele et al., 2023a; Kawhena et al., 2021; Weber et al., 2015; Yahia et al., 2019b). In most apple cultivars, higher levels of CO_2 and low oxygen concentration can slow down apple respiration within the storage environment. Typically, the O_2 level is decreased to about a1-10% while the CO_2 level is increased to about 1-10% depending on the storage condition involved and the cultivar (Du et al., 2021; Thewes et al., 2020). At these concentration levels, the ripening of the apple fruits, which is normally caused by the release of the ethylene gas by the fruits, becomes reduced and therefore reduces the respiration rate and the ripening. Therefore, apples that are stored in a controlled atmosphere will experience a reduced ripening rate due to the low amount of O_2 and CO_2 in the environment and will continue to maintain their freshness as well as their quality characteristics like colour and nutritional values.

However, findings from primary research have shown that, in controlled atmospheric storage, there is a gradual decrease in the apple's flavour profile, particularly its aroma, especially when stored for extended periods like six months or more (Lee et al., 2022; Thewes et al., 2020). Another challenge, as revealed by a study, is the potential development of physiological disorders under CA storage conditions, which may vary among different apple cultivars (Büchele et al., 2023b). Studies have also shown that storing a particular cultivar outside its recommended conditions can exacerbate physiological damage (Prange & Wright, 2023; Wood et al., 2022). For instance, a study revealed that elevated levels of CO_2 triggered browning disorder on the skins and flesh of water-colored apples during pulsed controlled atmosphere storage (Du et al., 2021). To mitigate CO_2 build-up during CA storage, some researchers have recommended the use of special CO_2 scrubbers or bags of hydrated lime (calcium carbonate) within the storage facilities or rooms, with the bags perforated to facilitate CO_2 absorption (Butkeviciute et al., 2022; D. S. Lee et al., 2022). Nevertheless, if the condition arises to store different or several cultivars in the same facilities, studies recommend that O_2 and CO_2 levels should always be adjusted to facilitate a favourable condition that will be suitable for the most sensitive cultivars (Büchele et al., 2024; Du et al., 2021).

3.9 Optimal Storage Conditions for Fresh-Cut Apples

Optimal storage technologies for fresh-cut apples play a crucial role in maintaining product quality and extending shelf life (P. Kumar & Sethi, 2021; Rodríguez-Arzuaga et al., 2021). One of the widely studied storage methods is modified atmosphere (MA) packaging, which aims to control the respiratory burst of cut apples, ethylene production rates, and softening while delaying microbial spoilage (Cozzolino et al., 2022; C. Xu et al., 2023). MA packaging is effective in reducing ripeness-related changes in cut produce, although its benefits are somewhat attenuated due to the shorter shelf life of these products compared to fresh whole fruits (Gil & Beaudry, 2020; Toivonen, 2020).

Temperature management is another critical factor in optimal storage. Appropriate storage temperatures for fresh-cut apples typically range from 1°C to 4°C (34°F to 39°F) as highlighted by a study (R. Soliva-Fortuny & Martín-Belloso, 2020b). Higher temperatures can significantly reduce shelf life due to increased respiratory activity, which varies depending on factors such as cultivar, physiological state, and postharvest handling (Kumar & Sethi, 2021; Shewa et al., 2022). Studies have shown that respiration rates and ethylene production in fresh-cut apples are greatly influenced by temperature variations (R. Soliva-Fortuny & Martín-Belloso, 2020b; Weber et al., 2020), highlighting the importance of maintaining consistent and optimal storage conditions.

In addition to temperature, the composition of the package atmosphere also plays a role in affecting respiration and product quality. Studies have shown that, low oxygen (O_2) atmospheres have been associated with reduced enzymatic browning in fresh-cut apples (Kumar & Sethi, 2021; Shrestha et al., 2020; Soliva-Fortuny & Martín-Belloso, 2020b), while elevated carbon dioxide (CO_2) concentrations can help reduce ethylene biosynthesis and related side effects (Wang et al., 2021), contributing to the preservation of product quality.

Various studies have explored different treatments and solutions to enhance the quality and shelf life of fresh-cut apples during storage. For instance, a study found that dipping apple slices in a solution containing ascorbic acid (AA) and citric acid (CA) was effective in limiting surface discoloration and inhibiting enzyme activity (Shrestha et al., 2020). Similarly, another study evaluated the performance of an antioxidant solution containing yerba mate, citric acid, and ascorbic acid in MAP storage, demonstrating its ability to reduce enzymatic browning, extend storage time, and maintain healthy compounds in fresh-cut apples (Rodríguez-Arzuaga et al., 2021). Ongoing research in this field continues to explore innovative strategies for improving storage technologies and preserving the quality of fresh-cut apples throughout the supply chain.

3.10 Modified Atmosphere Packaging (MAP)

Modified Atmospheric Packaging has been used for the preservation of freshness and nutritional values of fruits and it has gain popularity as a food preservation method due to its minimal impact on the attributes of fresh apple fruits (Cliff, Toivonen, Forney, Liu, et al., 2010). This preservation technique involves replacing the air surrounding the food in the package with an atmosphere of different composition (Gorris & Peppelenbos, 2020; McMillin, 2020). MAP aids in extending the shelf life of perishable products like fruits and vegetables by delaying the physicochemical changes associated with quality loss (Xu et al., 2023).

In this technique, the atmosphere composition within the package is primarily determined by the type of product, as well as the packaging materials and storage temperature as highlighted by several studies (Gorris & Peppelenbos, 2020; McMillin, 2020). Given that fruits and vegetables respire, their preservation is of particular importance. The packaging film's permeability to O_2 and CO_2 must be appropriate for the specific respiration rate of the product in order to establish a balance of modified atmosphere within the package (Czerwiński et al., 2021; Gorris & Peppelenbos, 2020). This storage technology is mostly used for fresh-cut products. For vegetables and fruits, the modified atmosphere typically contains low O_2 and high CO_2 levels when compared to those in the normal air (Fang & Wakisaka, 2021), and this regulated air slows down the normal respiration rate and extends the product shelf life.

This technique can be employed to extend the storage period of minimally processed fresh-cut apples thereby maintaining the original freshness of the apple fruits, as it effectively slows down the natural deterioration process of apple products (Cortellino et al., 2015). The use of this technology can result in prolonged shelf life and enhance the appearance of the apple cuts, making the product more appealing to consumers. However, it is important to note that MAP may not significantly enhance the values of low-value fresh produce (Pinto et al., 2020). Also, proper hygiene and temperature control during the chilling phase are essential for preserving the qualities and extending the shelf life of modified atmosphere packaged products (McMillin, 2020; Moradinezhad, Ansarifar and Moghaddam, 2020). Furthermore, the gas composition inside the package changes over time due to the exchange of air and the influence of microorganism growth (O Caleb et al., 2013) therefore, the gas composition must be carefully monitored and replaced to ensure that the concentration is adequate for the packaged product (McMillin, 2020). The specific gas mixture used in MAP depends on the type of produce, the packaging material, and the package temperature (Gil & Beaudry, 2020). Since fresh apples or fruits respire, it is crucial to consider the interaction between the packaging material and the product to ensure the effectiveness of MA packaging.

In this technique, balancing gas composition is crucial, because excessive oxygen accelerates ripening (Gundewadi et al., 2018b), while insufficient oxygen can lead to anoxic conditions, promoting off-flavour due to fermentative processes (Wood et al., 2022). Similarly, controlling moisture levels is essential to preserve the desired texture and inhibit microbial growth (Qu et al., 2022). Also, packaging materials can be tailored to regulate gas permeability, either through material selection or by introducing perforations (Chowdhury et al., 2017). Studies have suggested the design of an effective package requires to pay attention of important factors like fruits respiration, storage conditions, material properties, and perforation characteristics (Lufu et al., 2021; Mukama et al., 2020; Qu et al., 2022).

The fundamental concept of MAP for fresh produce like apples involves the replacement of air around the product inside a package within a specific combination of gases. The alteration is carefully controlled to maintain a desired set point and balance (Cortellino et al., 2015; P. Kumar & Sethi, 2021). MAP is particularly complex for fresh produce due to the ongoing respiration of the products, where they consume oxygen and release carbon dioxide. Research findings (Caleb et al., 2013) show that this technology has successfully been used to maintain the quality of fresh-cut apple products.

Some studies have highlighted several benefits of using MAP including: (Caleb et al., 2013; Cukrov et al., 2019; Qu et al., 2022), they include, but are not limited to:

1. It increases the shelf life of the fresh produce.
2. It increases food availability and reduces food wastage.
3. It reduces manufacturing and packaging costs.
4. It maintains a good structural arrangement for cutting fresh fruits.
5. It promotes the use of little or no chemical preservatives.

However, some studies have noted several limitations which are associated with this technique especially in terms its capital-intensive nature and costly maintenance because it requires the use of advanced materials and equipment (Bodbodak & Moshfeghifar, 2016).

Nevertheless, the benefits of using this technique in storing fresh fruits significantly outweighs the limitations and that is why it is still being employed in numerous researches.

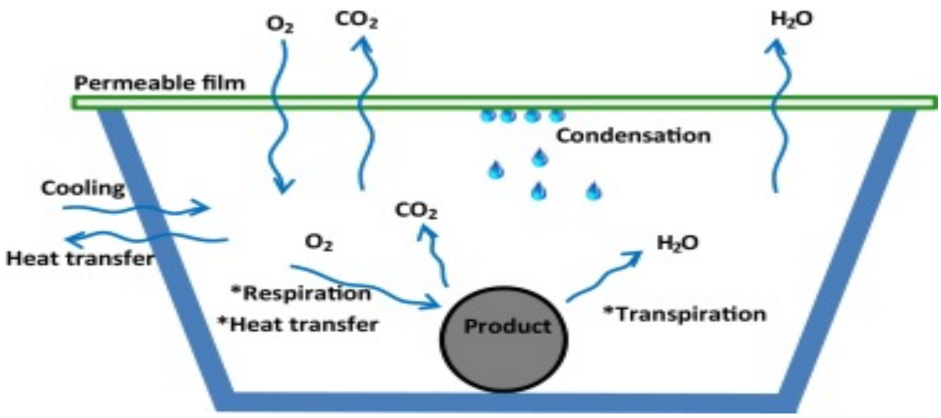

Figure 5. Mechanism of Modified Atmosphere Packaging (Belay et al., 2016)

3.10.1 Gases Applied in MAP

Modified Atmosphere Packaging (MAP) utilizes a combination of gases to create an optimal environment for product storage. The composition of these gases in the package is precisely reliant on the fresh produce that needs to be preserved (McMillin, 2020). The gases can also be used solely or in combination with the sole aim of prolonging the shelf life of the product. The three most commonly used gases in MAP are oxygen (O_2), carbon dioxide (CO_2), and nitrogen (N_2) (Floros & Matsos, 2005). O_2 is consumed during product storage, while CO_2 is generated as a byproduct of produce respiration (Ares et al., 2007). Nitrogen serves as an inert filler gas in MAP, balancing the volume decrease caused by CO_2 absorption and preventing package collapse (Priyadarshi et al., 2020). Typically, an atmosphere containing 3-6% O_2 and 2-10% CO_2 is used to achieve microbial control and extend the shelf life of fresh-cut products (Pan et al., 2015; Wei et al., 2020). Additionally, noble gases such as helium, argon, and xenon, along with nitrous oxide (N_2O), have been employed in MAP applications to further reduce microbial growth and maintain product quality (Zhang et al., 2016), highlighting the versatility and effectiveness of gas combinations in modified atmosphere packaging.

As highlighted by a study, details of the MAP gas used on the label, in line with the EU regulation 95/2/EC should be ideally listed as their corresponding E number (Oxygen: E948, Nitrogen: E941, Argon: E938 and Carbon dioxide: E290) (McMillin, 2020).

3.10.2 Respiratory Kinetic Models in Modified Atmosphere Packaging

Respiratory kinetics in modified atmosphere packaging (MAP) plays a critical role in determining the shelf life and quality of perishable produce. A study (Ghosh & Dash, 2020) elucidated that respiration rates are commonly measured by observing the concentrations of oxygen (O_2) consumption or carbon dioxide (CO_2) evolution per unit time per unit weight (mL kg−1 h−1) of specific produce. From a kinetic standpoint, respiration can be evaluated using three primary methods: (1) measuring O_2 consumption and CO_2 production rates within cells, (2) assessing O_2 mass transfer between fruit cellular solutions and the environment, and (3) studying the mass transfer of CO_2 from cellular solutions to the ambient atmosphere.

Another study (Badillo & Segura-Ponce, 2020) highlighted two prevalent approaches in MAP modeling: classic MAP modeling and numerical modeling. Classic MAP modeling, as presented in a study, relies on mass balance equations to model O_2 and CO_2 gas concentrations in the headspace of packaging. This approach assumes a stable state within the MAP environment (Hayakawa et al., 1975). Conversely, numerical modeling involves advanced computational techniques to simulate gas exchange dynamics in MAP, considering variations in gas concentrations between internal and external atmospheres (Belay et al., 2016).

A pivotal advancement in respiratory kinetics modeling has been the incorporation of enzyme kinetics models. A study (Lee et al., 1991) initially introduced enzymatic kinetic models to study respiration rates, with the Michaelis–Menten model (MM) without inhibition emerging as a fundamental tool in MAP designs (Ersan et al., 2009; Mahajan & Caleb, 2017). This model, based on substrate-enzyme interactions, provides valuable insights into the factors influencing respiration rates and gas exchange in MAP.

Furthermore, another study emphasized that gas exchange in modified atmosphere packaging is driven by differences in gas concentrations between the external and internal atmospheres of plant organs (Ho et al., 2018). Recent decades have witnessed significant progress in predicting respiratory kinetics, with enzyme kinetics models serving as the cornerstone for technological advancements in MAP (Belay et al., 2016).

The table below shows the different respiratory models that have been used by numerous authors in calculating the kinetic respiration rates of different fruits:

Model	Respiration model	Parameters	Packaging system	Fruit or vegetable	Concentration C_{O_2}	Concentration C_{CO_2}	Storage temperature T (°C)	References
Exponential model	$R_{O_2} = A_1 \text{Exp}\,(-A_2 \cdot C_{CO_2}) \cdot C_{O_2}$ $R_{CO_2} = k_1(A_1 \text{Exp}(-A_2 \cdot C_{CO_2}) \cdot C_{O_2})$ $A_1 = \frac{ml}{kg\ h}$	$(PF1): A_1 = 3.25$ $(PF1): A_2 = 0.971$ $(PF1): k_1 = 0.913$	Permeable system: olyolefines (PF1)	Iceberg lettuce	21 (%)	0.03 (%)	5	[16]
		$(A): A_1 = 3.41$ $(A): A_2 = 0.595$ $(A): k_1 = 1.07$	Permeable system:	Golden delicious apple	5 (%)	5 (%)	4	[74]
	$R_{O_2} = \alpha_1(A_1 \text{Exp}(-A_2 \cdot C_{CO_2}) \cdot C_{O_2})$ $R_{CO_2} = \alpha_2(A_1 \text{Exp}(-A_2 \cdot C_{CO_2}) \cdot C_{O_2})$	$\alpha_1 = 5.0$ $\alpha_2 = 2.9$	Permeable system (PA/PE)	Cactus pear	21 (%)	0.03 (%)	4	[25]
	$A_1 = 1.0e^{-6} \left(\frac{ml}{kg\ h}\right)$ $A_2 = 2.84e^{-3}(-)$	$\alpha_1 = 9.5$ $\alpha_2 = 8.5$			21 (%)	0.03 (%)	8	
	$\alpha_1\ (-);\ \alpha_2\ (-)$	$\alpha_1 = 8.5$ $\alpha_2 = 7.5$			10 (%)	10 (%)	8	
Michaelis–Menten (MM) Michaelis–Menten uncompetitive (MMU)	$R_{O_2} = \frac{V_{max} \cdot C_{O_2}}{k_m + C_{O_2}}$	V_{max}= 0.62 k_m= 6.6	Closed system	Cherry tomatoes	21 (%)	0.03 (%)	5	[55]
	$V_{max}\left(\frac{ml}{kg\ h}\right);\quad k_m(\%)$	V_{max}= 0.95 k_m= 5.7					10	
		V_{max}= 1.62 k_m= 14.5					15	
		V_{max}= 2.91 k_m= 12.9					20	
	$R_{O_2} = \frac{V_{max} \cdot P_{O_2}}{k_m + P_{O_2}}$ $V_{max} = \frac{mol}{kg\ h}; k_m\ (atm); P_{O_2}(atm)$	V_{max}= 17.6x10^{-4} k_m= 0.71	Closed system	Burlat cherries	1.85 (%)	4.69 (%)	5	[75]
	$R_{O_2} = \frac{V_{max} \cdot C_{O_2}}{k_m + C_{O_2}}$ $V_{max} = A \cdot \text{Exp}(-E_a/RT)$ $V_{max}\left(\frac{ml}{kg\ h}\right);\ E_a\left(\frac{kJ}{kg}\right); k_m(\%)$	V_{max}= 1.6x10^{13} k_m= 0.19 $E_a = 64.2$ A= 1.6x10^{13} $A\left(\frac{ml}{kg\ h}\right)$	Pervious system	Strawberries	21 (%)	0.04 (%)	10	[64]
	$R_{O_2} = \frac{V_{max} \cdot P_{O_2}}{k_m + \left(1 + \frac{P_{CO_2}}{k_u}\right) P_{O_2}}$ $V_{max} = \frac{ml}{kg\ h}; k_m\ (kPa); P_{O_2}(kPa)$ $P_{CO_2}(kPa); k_u(kPa)$	V_{max}= 4.51 k_m= 4.72 k_u= 11.31	Closed system	Guava fruit	21(%)	0.03 (%)	5	[76]
		V_{max}= 7.78 k_m= 7.17 k_u= 10.23					10	
		V_{max}= 12.04 k_m= 14.03 k_u= 9.04					15	
		V_{max}= 19.43 k_m= 17.39 k_u= 8.11					20	
		V_{max} = 30.18 k_m= 19.42 k_u= 7.89					25	
		V_{max}= 36.03					30	

Model	Respiration model	Parameters	Packaging system	Fruit or vegetable	Concentration C_{O_2}	Concentration C_{CO_2}	Storage temperature T (°C)	References
	$R_{O_2} = \frac{V_{max} \cdot C_{O_2}}{k_m + \left(1 + \frac{C_{CO_2}}{k_u}\right) C_{O_2}}$ $V_{max} = A \cdot \text{Exp}(-E_a/RT)$ $V_{max} = \frac{ml}{kg\ h}; k_m\ (\%); C_{O_2}(\%)$ $C_{CO_2}(\%); k_u(\%)$ $E_a\left(\frac{kJ}{kg}\right) = 28.32$ A= $4.1x10^6$	k_m= 21.34 k_u= 6.88 V_{max}= 12.20 k_m= 3.64 k_u= 14.11 V_{max}= 14.05 k_m= 4.93 k_u= 11.05 V_{max}= 16.29 k_m= 6.6 k_u= 10.01 V_{max}= 21.61 k_m= 7.46 k_u= 8.50 V_{max}= 27.02	Closed system	Sopota fruit	21 (%)	0.03 (%)	0 5 10 15 20	[72]
	$R_{O_2} = \frac{V_{max} \cdot P_{O_2}}{k_m + \left(1 + \frac{P_{CO_2}}{k_u}\right) P_{O_2}}$ $V_{max} = A \cdot \text{Exp}(-E_a/RT)$ $V_{max} = \frac{ml}{kg\ h}; k_m\ (kPa); P_{O_2}(kPa)$ $P_{CO_2}(kPa); k_u(kPa)$ $E_a\left(\frac{kJ}{kg}\right) = 42.20; 43.4; 45.8$ A= 46; 47; 49	k_m= 8.51 k_u= 8.10 V_{max}= 44.32 k_m= 2.14 k_u= 1.83 V_{max}= 45.83 k_m= 3.28 k_u= 1.24 V_{max}= 49.48	Closed system	Capsicum	21 (%)	0.03 (%)	10 15 20	[7]
	$R_{O_2} = \frac{V_{max} \cdot C_{O_2}}{k_m + \left(1 + \frac{C_{CO_2}}{k_u}\right) C_{O_2}}$ $V_{max} = \frac{ml}{kg\ h}; k_m\ (\%); C_{O_2}(\%)$ $C_{CO_2}(\%); k_u(\%)$	k_m= 3.92 k_u= 1.32 V_{max}= 4.306 k_m= 2.31 k_u= 4.252 V_{max}= 5.431 k_m= 2.92 k_u= 3.638 V_{max}= 8.549 k_m= 3.34 k_u= 2.645 V_{max}= 28.58 k_m= 4.11 k_u= 1.33 V_{max}= 36.76	Closed system	Bhimkolbanana	21 (%)	0.03 (%)	15 20 25 30 35	[58]
Michaelis–Menten uncompetitive (MMU)	$R_{O_2} = \frac{V_{max} \cdot C_{O_2}}{k_m + \left(1 + \frac{C_{CO_2}}{k_u}\right) C_{O_2}}$ $V_{max} = A \cdot \text{Exp}(-E_a/RT)$ $V_{max} = \frac{ml}{kg\ h}; k_m\ (\%); C_{O_2}(\%)$	k_m= 5.20 k_u= 1.21 V_{max}= 36.76 k_m= 1.9 k_u= (−)	Closed system	Strawberries	21 (%)	0.03 (%)	10 19 23	[77]

Figure 6. Respiratory Kinetic Models Used by Other Authors

This table was adapted from a study (Badillo & Segura-Ponce, 2020). See Appendix 1 for the outlined reference of each study in the table above.

3.10.3 Microperforation in Modified Atmosphere Packaging of Fresh-Cut Apples

Micro-perforation involves creating some small holes in the packaging film, which allows for the buildup of adequate carbon dioxide and oxygen levels to establish a safe environment for the product being packaged (Genesis, 2015; Oliveira et al., 2022). Using micro-perforation for MAP with the aim of evaluating the respiration of fresh-cut apple fruits has been used and has shown some effective contribution to the microbiological safety of fresh-cut apple produce (Ghidelli & Pérez-Gago, 2018a; Hussein, Caleb, & Opara, 2015a), highlighting the role of innovative strategies such as the retardation of produce respiration rate and delaying enzymatic degradation of complex substrates.

The key effects of micro-perforation on packaged products include (Hussein, Caleb, Jacobs, et al., 2015; Vega-Diez et al., 2024):

1. It reduces the risk of Anaerobic and associated microbial growth.

2. It facilitates a conducive environment for the product due to the constant maintenance or build-up of carbon dioxide and oxygen levels.
3. It helps to maintain the product's qualities and extend its shelf life by controlling the respiration rate.

Micro-perforation films (perforation) offer a solution for achieving the desired gas composition in modified atmosphere packaging (Hussein, Caleb, Jacobs, et al., 2015), and is particularly beneficial for fresh-cut apple products. Perforation helps to enhance the modification atmosphere packaging versatility by dynamically promoting and controlling the internal atmosphere composition, and this helps in the prolongation of fruits and vegetables with high respiration rate (Caleb et al., 2018). It has been used in different or widespread application in the modified atmosphere packaging (MAP) of highly respiring fresh apple fruits as highlighted in different studies (Badillo & Segura-Ponce, 2020; González-Buesa & Salvador, 2022). The perforation in a film plastic serves as a polymeric film in regulating gas exchange (González et al., 2008).

Several studies have shown that, the use of this technology will lead to better qualities, reduce decay and improve flavour of fresh-cut apples by regulating the gas composition within the package (Ghidelli & Pérez-Gago, 2018a; Hussein, Caleb, Jacobs, et al., 2015). Nevertheless, researchers have pointed out that food producers must always pay attention to the perforation methods because the microstructure of the perforation depends on the method and the type of polymeric film used in the perforation (Hussein, Caleb, & Opara, 2015a). A study that used a laser tube perforation in MAP of fresh produce noted that the optimum perforation parameters depend on the respiration coefficient of the packaged materials, which can fluctuate between the ranges of 0.7 and 1.3 (Hussein, Caleb, & Opara, 2015a).

3.11 Quality Parameters and Changes in Apples in Relation to Respiration

The respiration process in apples plays a crucial role in determining various quality parameters such as texture, flavor, appearance, nutritional composition, and the occurrence of physiological disorders (Andrich et al., 1991, 1998; Mishra & Gamage, 2020). Temperature, as highlighted in numerous studies, directly influences respiration rates in apples which in turn impacts these quality aspects (Ahmad et al., 2021; Johnston et al., 2001; Mangaraj & Goswami, 2008). Studies have shown that apples stored at lower temperatures exhibit reduced respiration rates, leading to slower enzymatic reactions and metabolic processes. This slower metabolic activity contributes to maintaining the texture of apples which in turn prevents excessive softening or breakdown of cell structures (Saquet & Streif, 2017; Weber et al., 2019; Wright et al., 2015). Additionally, the flavor profile of apples is influenced by respiration rates as studies have highlighted that slower rates are often associated with better retention of natural flavors and aromas (Ting et al., 2016; Wright et al., 2015).

Nutritional composition is another key area affected by apple respiration. The metabolic processes during respiration involve the breakdown of organic substrates, including carbohydrates, lipids, and organic acids (Brizzolara et al., 2020; Saltveit, 2019). Research has found that the availability and breakdown of these compounds influences the nutritional content of apples such as sugar levels, vitamin content, bioactive compounds, and antioxidants (Bondonno et al., 2017; Mushtaq, 2022). Study also revealed that apples stored under optimal respiration conditions can retain higher nutritional value compared to those stored at higher temperatures with increased respiration rates (Sumedrea et al., 2018).

However, excessive respiration rates or storage conditions that lead to metabolic imbalances can result in physiological disorders. For instance, studies have linked the occurrence of storage disorders like bitter pit, cork spot, discoloration and brown core to changes in respiration rates and biochemical activities (Büchele et al., 2023b; K. P. Singh & Aravind, 2021; Thompson et al., 2018). Factors such as calcium ion concentrations, ethylene evolution and enzyme activity which are influenced by respiration can contribute to the development of these disorders (Gundewadi et al., 2018b; Y. Xu et al., 2022). Understanding the relationship between respiration and physiological disorders is therefore essential for implementing storage strategies that minimize these issues and maintain overall fruit quality.

3.12 Innovations and Advancements in Apple Respiration Studies

Research on apple respiration has come a long way in the last few years, with an emphasis on improving postharvest quality and increasing shelf life. Developing unique storage technologies and methods to control apple respiration rates and metabolic activities is one noteworthy field of innovation (Thewes et al., 2017). These developments are very important in tackling obstacles like preserving texture, flavor, and nutritional value while reducing physiological imbalances during storage.

One particularly interesting development in apple respiration research is the Dynamic Controlled Atmosphere (DCA) technology. Research has compared the quality of apples stored with DCA to typical static controlled atmosphere (CA) storage, with studies some studies (Büchele et al., 2023b; Weber et al., 2015, 2019) evaluating the apples' quality. Based on real-time observations, DCA systems actively modify gas compositions to optimize conditions and reduce respiration rates and ethylene production. Fruit quality has been enhanced overall as a result of this creative method, which has demonstrated promising outcomes in maintaining apple firmness, decreasing weight loss, and inhibiting CO_2 formation as evidenced by study findings (Büchele et al., 2023b; Weber et al., 2019).

Our knowledge of the kinetics of apple respiration has also been completely transformed by developments in kinetic research and mathematical modeling. Enzyme kinetics models have been employed by researchers such some studies (Mangaraj & Goswami, 2008) to forecast respiration rates at varying temperatures, offering significant understanding of the correlation between carbon dioxide and oxygen concentrations. In addition to aiding in the optimization of storage conditions, these models are useful in the development of strategies aimed at mitigating metabolic imbalances and decreasing the incidence of physiological issues in apples and other fruits (Ghosh & Dash, 2020; Karacabey & Buzrul, 2017). Additionally, to improve apple quality after storage, creative interventions and treatments have also been investigated. Low magnetic fields may be used to enhance apple quality and prolong shelf life, according to research (Saletnik et al., 2022). This research study showed that constant magnetic field treatment produced apples with increased firmness, decreased weight loss, and suppressed CO_2 production, all of which indicated greater prospective quality overall.

Research has also been done to better understand the biochemical and molecular processes that underlie apple respiration. Research on enzyme activities, metabolic pathways, and the impact of calcium ion concentrations on respiration rates and the incidence of storage diseases have been conducted several studies (Cozzolino et al., 2022; Cukrov et al., 2019). The development of focused interventions and management techniques to maximize apple respiration and preserve fruit quality is aided by these developments.

In general, postharvest management techniques will continue to change as a result of the continuous discoveries and breakthroughs in the field of apple respiration research. As a result of these advancements, we are better equipped to comprehend physiological processes and develop more effective and sustainable methods for improving apple quality, cutting waste, and satisfying consumer demand for wholesome, fresh apples.

3.13 Literature Gap

The reviewed literature offers a thorough summary of many elements of apple respiration, such as the impact of temperature, cutting-edge storage techniques, biochemical processes, and quality factors. Nonetheless, this research study has the potential to fill several gaps in the body of current information. A noteworthy gap is the restricted investigation of particular genetic variables or cultivar variants that could influence apple respiration rates and postharvest quality. This study offers to close this gap by researching a particular apple cultivar. Gaining knowledge about how specific apple types react to storage conditions and how their genetic composition affects respiration dynamics may help to optimize storage procedures and improve fruit quality.

Furthermore, although the literature covers the effects of temperature and controlled atmosphere storage on apple respiration, more research is needed to determine the impacts of innovative storage methods, like dynamic controlled atmosphere (DCA), on apple respiration and quality attributes. Also, to improve the effectiveness of storage techniques, it may be interesting to investigate the synergistic effects of several gases, particularly noble gases like argon and helium, and their use in modified atmosphere packaging (MAP). Filling these gaps in the literature could, in general, greatly advance our knowledge of apple respiration and enhance fresh product postharvest management practices.

4.0 MATERIALS AND METHOD

4.1 Methodological Overview

After harvest, the apple fruit has strong respiration and metabolic activities, which easily induce quality deterioration, shortening the storage period and shelf life, which affects the farmers' income. To understand the quality change mechanisms of apples and extend the storage period, this study analyzed the fruit respiration and texture of *Malus domestica* Borkh. cv. 'Idared' varieties by cutting them into slices, storing the slices in a plastic foil, and monitoring them during storage at 5°C. This methodology aimed to investigate the respiration conditions, including packaging and controlled temperature of apple slices. The use of a Multivac T200 sealing machine allowed for precise sealing, while the controlled temperature in the storage environment provided a stable setting for observing changes in oxygen gas over the storage period. The methodology was designed to assess the efficiency of the packaging and the impact of storage conditions on the respiration rates of the apple slices, to gain insights into the optimal storage conditions for maintaining the quality and freshness of the apples. This research methodology draws from established principles of apple storage and respiration, as well as practical considerations for conducting controlled experiments to evaluate the impact of storage conditions on the respiration rates of apple slices.

4.2 Study Location

This research study was carried out at the postharvest laboratory of the Department of Postharvest, Commerce, Supply Chain, and Sensory Science at the Institute of Food Science and Technology at the Hungarian University of Agriculture and Life Sciences (MATE) in Budapest, Hungary.

4.3 Sample Preparation

Five (5) apples of the cultivar: *Malus domestica* Borkh. cv. 'Idared' were carefully selected based on size, colour, and absence of physical damage. The selected apples were thoroughly washed in running water to ensure cleanliness and no colour fixation was used in the washing process. Subsequently, the apples were manually cut into slices of approximately 1 cm thickness with a knife. To prevent discoloration of the cut surface, the apple slices were immersed in a bowl of normal tap water, and excess water was removed from the surface using a tissue during the arrangement of the slices in the transparent and rectangular foil tray (0.1016 by 1.127 meter) together with an oxygen gas checker named Watch Gas SST1 which was manufactured by Watch Gas in Rotterdam, Netherland (size 83*49*20mm, weight 88g, sensor measuring range 0.2-0.25% by vol, temperature range -40 +60 ^{0}C). It is used because it has a large screen, is simple to operate, and easy to read. The practical was carried out at the Postharvest laboratory of the Department of Postharvest, Commerce, Supply Chain and Sensory Science at the Hungarian University of Agriculture and Life Sciences (MATE) in Budapest, Hungary.

Figure 7. Sliced Apples Immersed in Water Before Packaging and Sealing

4.3.1 Experimental Design

The experimental design for this study involved the use of three distinct samples, each assigned randomly and given unique sample names to ensure anonymity and eliminate bias in the experimental process. The table below shows the variations in each sample:

Table 1. Experimental Design of Samples

Samples	**Sample Weight**	**Perforation Measurements**
Sample A	75.34 g	L= 455.312µm A=12286.768µm ^{2}
Sample B	74.81 g	L= 491.090µm A= 14725.077µm ^{2}
Sample C	75.47 g	L= 522.96µm A= 15883.342µm ^{2}

L= Length; A=Area

4.3.2 Packaging and Sealing

The storage samples, weighing 75.34 g, 74.81 g, and 75.47 g, respectively for samples 12.760, 14.725, and 14.836, which is inclusive of the storage containers, were manually packed together with an oxygen gas checker and sealed using a Multivac T200 (400V, 50Hz, 4.3 kW) sealing machine manufactured by Multivac in Wolfertschwenden, Germany. This equipment was used because it is built with well-established quality components that have proven reliable over Multivac's decades of industry experience. The sealing efficiency of the packages was manually evaluated, and micro-perforation was performed to check the area of the hole in the package with a laser perforator machine (Laser plotter CO_2 50w DSP 40 *60 cm CL6040T, manufactured by Shanghai ZX Trading Co. limited, Shanghai, China) with a single setting of a speed 25mm/s, 100% power, and size 1.101mm. The laser micro-perforation generate monochromatic, coherent, and directional beam of light that caused a whole on the penetrated surface of the package, thus inducing little to minimal damage without causing any mechanical contact on the apple fruits used (Hussein, Caleb, & Opara, 2015b), this process was monitored by a digital microscope (Dino-lite Edge AM7515MT4A, manufactured by AnMo Electronic Corporation, New Taipei City, Taiwan) and it was able to determine the smallest perforation space on the package due to its fastness and smooth capturing of high qualities images and an impressive range of special speed features of 45fps at 1280*960 resolution.

Figure 8. Oxygen Gas Checker

Figure 9. Multivac T200 Sealing Machine

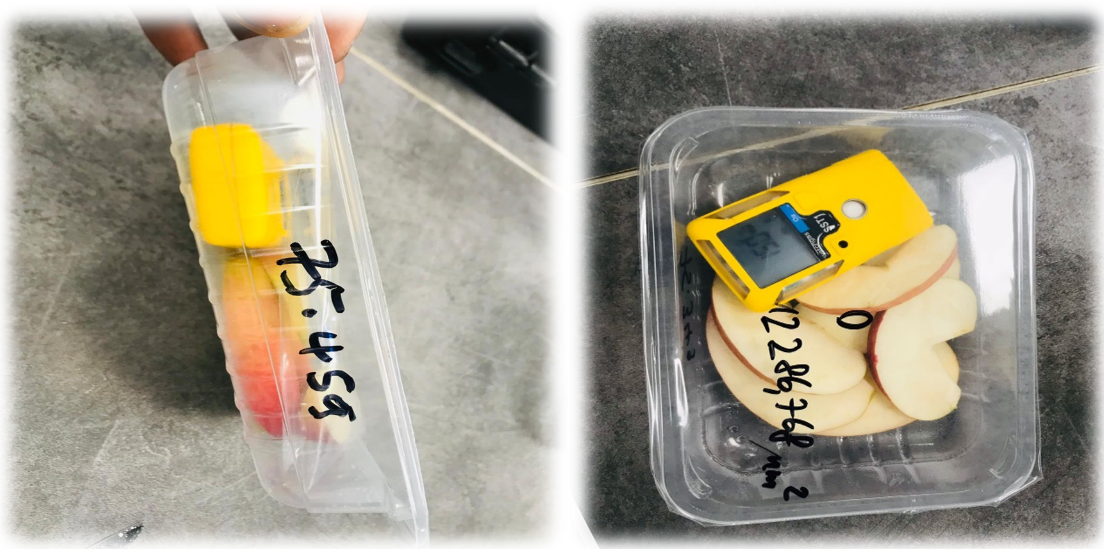

Figure 10. Packaged and Sealed Apple Samples

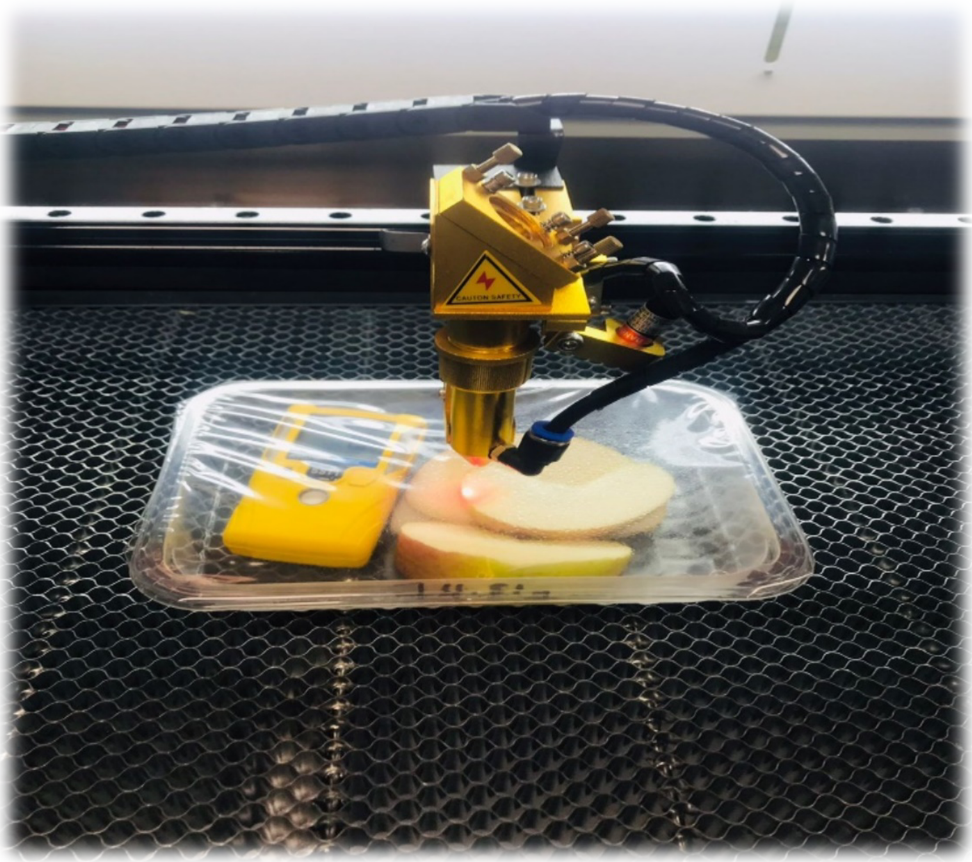

Figure 11. Laser Perforator Machine

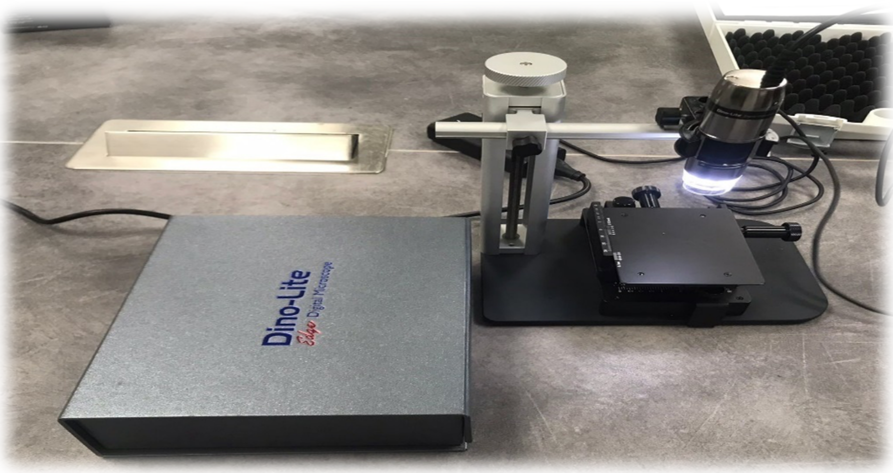

Figure 12. Digital Microscope used in Monitoring Perforation Process

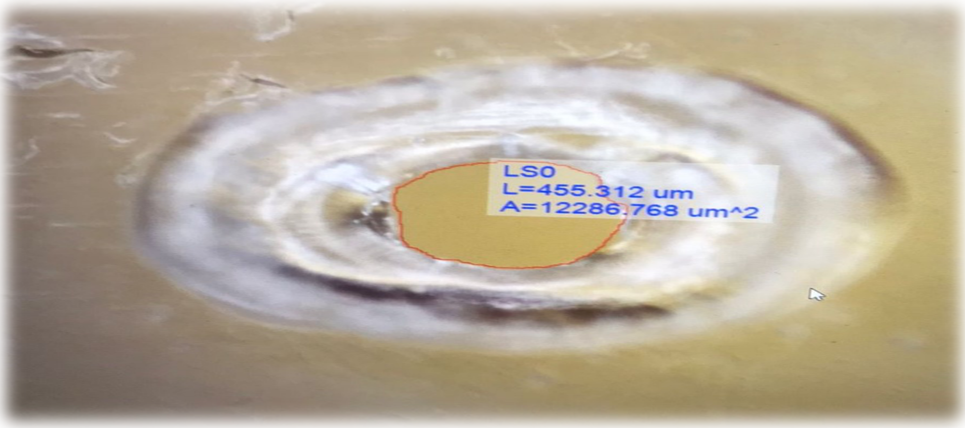

Figure 13. Perforation of Sample A

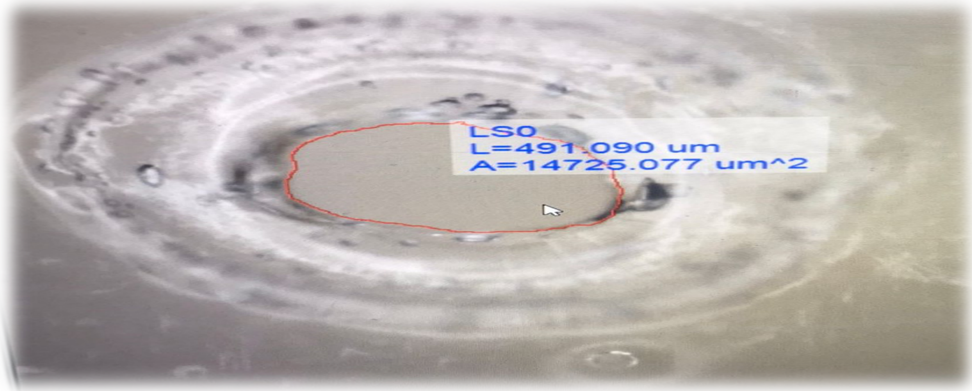

Figure 14. Perforation of Sample B

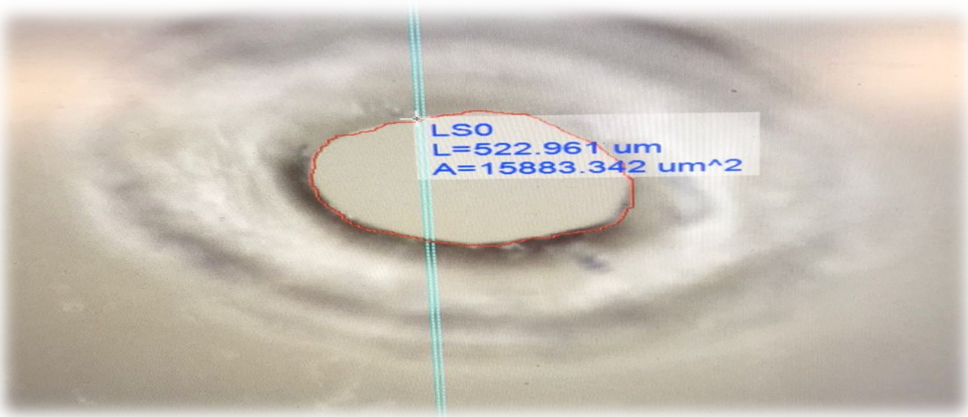

Figure 15. Perforation of Sample C

4.3.3 Storage Conditions

The sealed packages containing the apple slices were stored in a fridge mounted inside with a GoPro camera (5.3k 60p) manufactured by GoPro Inc. in Hubei, China. This camera was used because it has an impressive high quality for video recording of the oxygen changes that was used for data extraction. Subsequently, the fridge was set with a controlled temperature of 5 °C. The storage period spanned seven (7) days, during which the relative humidity of the atmosphere was constant. All experiments were carried out in triplicate to ensure the reliability and consistency of the results.

Figure 16. Camera Mounted in the Storage Fridge

Figure 17. Sample In Refrigerated Storage

Figure 18. Samples After 7 Days Storage Period

4.4 Data Collection

Over a 7-day storage period, data was collected on changes in oxygen changes, time differences, and oxygen differences of each sample. The data was recorded at an approximate time interval of 30 minutes using the recording of the Watch Gas SST1 oxygen gas checker sealed within the sample containers and the video evidence from the GoPro camera. This time interval was reflective of every time the apple respired.

4.5 Data Analysis

The data collected for this research project was subjected to thorough analysis using Microsoft Excel. Data models were generated by plotting graphs and incorporating trend lines. Trend lines were added to the graphs to highlight patterns and relationships within the data, thereby providing valuable insights into the respiration patterns of apples under different storage conditions. Also, Microsoft Excel was used to compute statistical parameters for the oxygen differences observed in each sample. The computed parameters included the mean, standard deviation, and mean deviation of the oxygen differences which were calculated using Excel's built-in functions. These statistical measures were crucial for understanding the variability and trends in the data, providing valuable insights into the respiration patterns of the fresh-cut apples for the study duration of 7 days.

5.0 RESULTS AND DISCUSSION

5.1 Introduction

The Results and Discussion chapter of this study will present a comprehensive analysis and interpretation of the gathered data regarding apple respiration rates under specialized storage conditions. The chapter will detail the numerical findings, showcasing graphical models and statistical analysis to illustrate trends and patterns observed during the experiment. Furthermore, the discussion section will critically evaluate these results in the context of existing literature and will go further to highlight similarities, differences and potential explanations for discrepancies between this study's findings and other findings of existing studies. Finally, the chapter will address the strengths and limitations of the methodology employed in this study and will offer insights into how these factors may have influenced the results and interpretations.

5.2 Results

5.2.1 Respiration Rate for Sample A

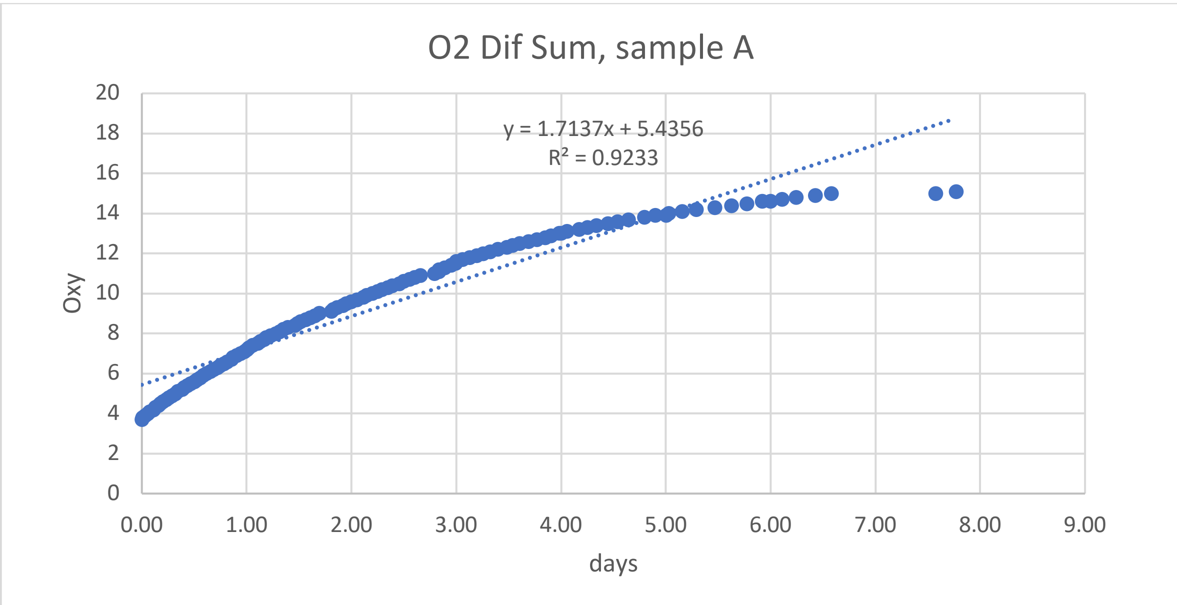

Figure 19. Graphical Model Showing Respiration Trend of Sample A

The graphical model above shows the respiration rate of sample A over a 7 days storage period at 5ºC. Graphically, the results show a clear trend in the respiration rate of the fresh-cut apple samples over the 7-day storage period. Initially, on Day 0, the respiration rate started at 3.7 units of oxygen, which is also reflected in the higher frequency of respiration (34 times). This rapid increase continued until Day 3, where the respiration rate peaked at 13 units and the frequency of respiration decreased to 15 times. After Day 3, the rate of increase in respiration became less rapid but remained steady until it reached 15.1 units on Day 7. However, an interesting observation is the significant reduction in the frequency of respiration over the days. It dropped to 24 times on Day 1 further decreasing to 20 times on Day 2, and then to 15 times on Day 3. This reduction continued and only 10 and 8 times of respiration was recorded on Day 4 and Day 5 respectively, and it further reduced to 5 times on Day 6 and finally 2 times on Day 7. The graph clearly shows an initial steep incline in both respiration rate which peaked around Day 3 and was followed by a gradual plateauing of the respiration till Day 7 which is indicative of the frequency in respiration rate and the overall steady increase in respiration rate across the days.

Additionally, the R^2 coefficient of this sample is 0.9233, and this indicates that there is a strong correlation between the time the apples were stored and their respiration rate which implies that the storage time had a significant impact on the respiration rate of fresh-cut apples.

Table 2. Statistical Results Based on the Respiration Rate of Sample A

Days	**Mean O_2 Difference**	**SD of O_2 Difference**	**MD of O_2 Difference**
0	5.400	1.025	0.874
1	8.350	0.707	0.600
2	10.550	0.592	0.500
3	12.300	0.447	0.373
4	13.450	0.303	0.250
5	14.250	0.245	0.200
6	14.800	0.158	0.120
7	15.050	0.057	0.050

SD= Standard Deviation; MD= Mean Deviation

The results presented in table 2 above shows the respiration rate of sample A of fresh-cut apples over seven days revealing distinct trends noted in the mean oxygen difference, standard deviation (SD), and mean deviation (MD). According to the results, on Day 0, the mean oxygen difference was 5.400, indicating an initial level of respiration, while Days 1 to 3 showed a substantial increase in respiration rates as seen in the mean oxygen differences of 8.350, 10.550, and 12.300, respectively. Notably, the SD and MD decreased progressively from Day 0 to Day 3, suggesting a tightening of data points around the mean and a more consistent respiration pattern. Days 4 to 6 saw a continued but moderated increase in respiration rates, with mean oxygen differences of 13.450, 14.250, and 14.800, respectively, and decreasing SD and MD values which indicates a more stable respiration. Significantly, on Day 7, although the mean oxygen difference further increased to 15.050, both SD and MD were at their lowest, signifying an exceptionally consistent and steady respiration rate.

5.2.2 Respiration Rate for Sample B

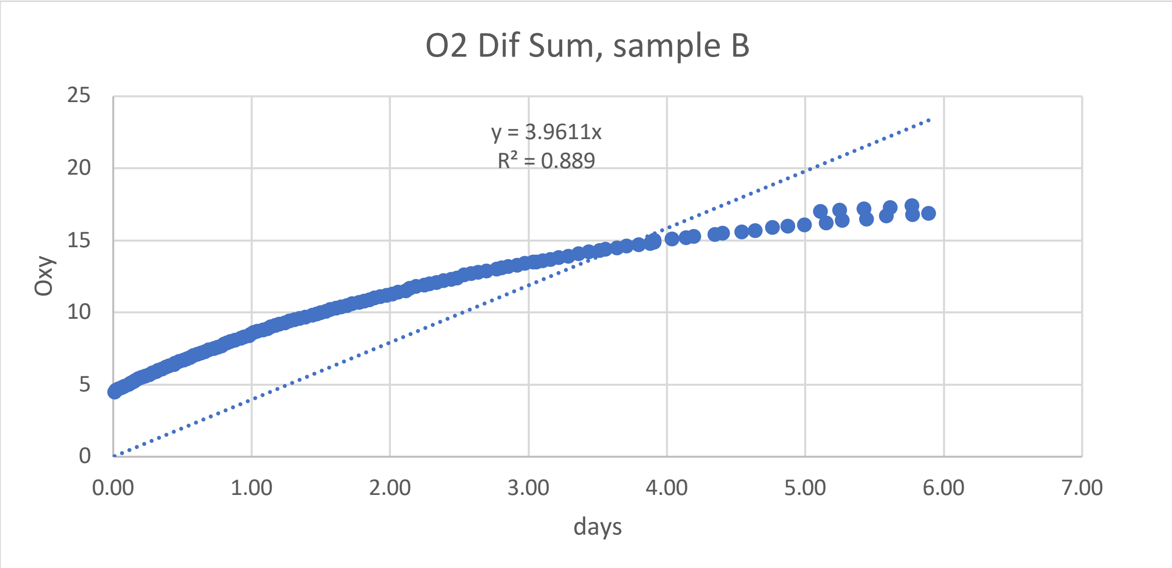

Figure 20. Graphical Model Showing Respiration Trend of Sample B

The graphical model presented above reveals the respiration rate of sample B over the observed 7days study and this result shows a distinct trend. The oxygen level started at 4.5 units on Day 0 and saw a rapid and substantial increase, reaching 11.2 units by the end of Day 1. This sharp rise suggests an initial burst of respiration activity. Subsequently, the rate of increase in respiration became more consistent, with oxygen levels climbing from 11.3 on Day 2 to 17.4 on Day 5. This steadier upward trend indicates a sustained respiration rate over these days. Notably, there was no record of respiration on Day 6 and Day 7. This absence of recorded respiration on Days 6 and 7 suggests a possible stabilization or plateauing of the respiration process at the observed temperature and conditions and is illustrated on the graph as a gap or flatline. Additionally, the frequency of respiration, which started at 41 on Day 0, decreased progressively over the observed days recording 28, 20, 16,11, and 3 times on Day 1, 2, 3, 4, and 5 respectively.

Furthermore, the graphical model presents an R^2 coefficient of 0.889 which indicates that there is a strong and highly significant correlation between the variables in the sample result.

In other words, there is a high degree of linear relationship between the storage days and the respiration rate.

Table 3. Statistical Results Based on the Respiration Rate of Sample B

Days	Mean O_2 Difference	SD of O_2 Difference	MD of O_2 Difference
0	6.500	1.198	1.024
1	9.900	0.794	0.674
2	12.380	0.659	0.560
3	14.219	0.500	0.431
4	15.580	0.343	0.280
5	16.367	0.153	0.111
6	0.000	0.000	0.000
7	0.000	0.000	0.000

SD= Standard Deviation; MD= Mean Deviation

Table 3 above presents the statistical results for the respiration rate of sample B over the 7 days study duration. The statistical results indicate a clear trend in respiration behavior. On Day 0, the mean oxygen difference was 6.500, with a standard deviation of 1.198 units and a mean deviation of 1.024 units. As the days progressed, the mean oxygen difference steadily increased, reaching 16.367 units on Day 5 while the standard deviation and mean deviations also continued to reduce across the days. The increase in respiration rate is reflected in the decreasing standard deviation and mean deviation, indicating a more consistent and predictable respiration pattern over time. However, it is important to note that on Day 6 and Day 7, there were no recorded values for the respiration rate, which could signify a cessation of respiration. This cessation of respiration could signify that certain factors may have led to a complete halt in respiration.

5.2.3 Respiration Rate of Sample C

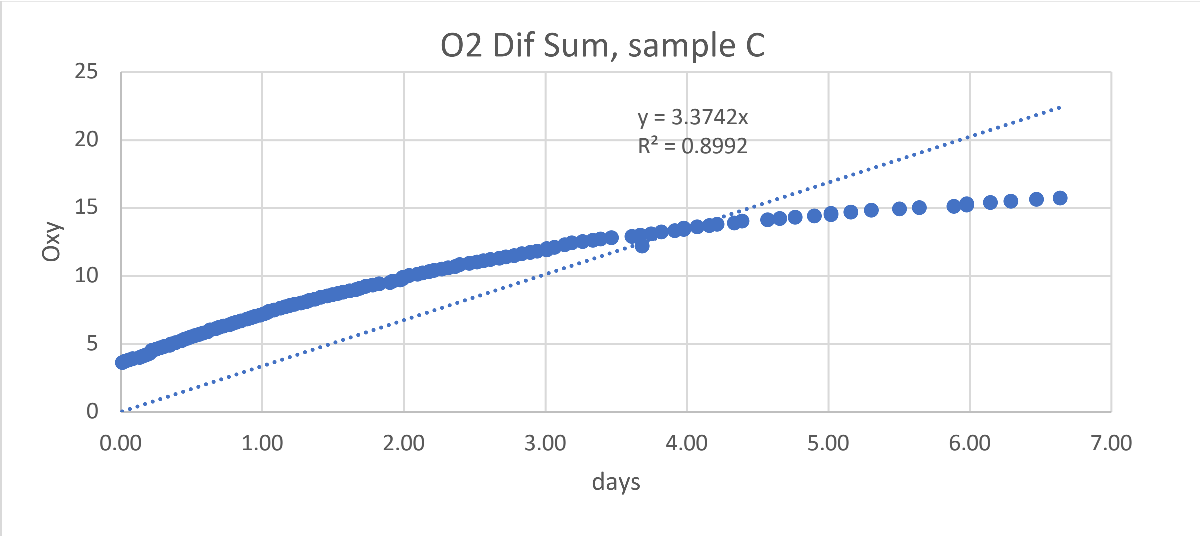

Figure 21. Graphical Model Showing Respiration Trend of Sample C

The result presented in the graphical model above show the respiration rate of sample C during the 7 days storage duration. Initially, on Day 0, the respiration rate started at 3.6 units of oxygen, which is also reflected in the higher frequency of respiration (35 times). The respiration rate increased rapidly to 9.9 units at the end of Day 1 while the frequency of respiration decreased to 28 times. The rapid increase to 9.9 units by the end of Day 1 suggests an accelerated metabolic activity, possibly due to the initial adjustment period. After Day 1, the rate of increase in respiration became less rapid but remained steady until it reached 15.7 units on Day 6. However, an interesting observation is the significant reduction in the frequency of respiration over the days. It dropped to 28 times on Day 1 further decreasing to 19 times on Day 2, and then to 17 times on Day 3. This reduction continued and only 9 times of respiration was recorded on Day 4 and Day 5, and it further reduced to 4 times on Day 6. This reduction in frequency may be indicative of a substantial decline in metabolic activity or a stabilization of physiological processes. Notably, there was no recorded respiration for Day 7 suggesting a process of metabolic stabilization or dormancy within the sample. The graph clearly shows an initial steep incline in respiration rate which peaked around Day 1 and was followed by a gradual plateauing of the trend lines till Day 6.

Furthermore, the graph shows that the R^2 coefficient is 0.992 which indicates that there is a strong and highly significant correlation between the time and oxygen variables. In other words, there is a high degree of linear relationship between the storage duration and the respiration rate.

Table 4. Statistical Results Based on the Respiration Rate of Sample C

Days	Mean O_2 Difference	SD of O_2 Difference	MD of O_2 Difference
0	5.350	1.054	0.900
1	8.550	0.823	0.700
2	10.900	0.563	0.473
3	12.700	0.505	0.424
4	14.000	0.274	0.222
5	14.900	0.274	0.222
6	15.500	0.129	0.120
7	0.000	0.000	0.000

SD= Standard Deviation; MD= Mean Deviation

The results presented in Table 4 above show the respiration rate dynamics of sample C the 7 days. The result shows an initial record of 5.350 for the value of the mean oxygen difference on Day 0 and notably, the respiration rate gradually increased as evidenced by the recorded 15.500 mean oxygen difference by Day 6. This upward trend is accompanied by a decrease in both standard deviation (SD) and mean deviation (MD) values over time, indicating a more consistent and predictable respiration pattern as the days progress. Interestingly, Days 4 and 5 show a plateau in the mean oxygen difference of around 14 units, suggesting stabilization of respiration rates during that period. The absence of recorded respiration on Day 7 is highlighted by all metrics registering zero values which signals a cessation in the respiration process for this sample.

5.3 Comparison of Results Between Samples

When comparing the results of the three different samples of fresh-cut apples which were stored under the same conditions but with varying micro-perforation sizes and sample weight, several notable trends have been identified. Firstly, there are notable differences in the respiration rates among the three samples despite the general trends of sharp increases followed by steadier phases. Sample A had a pronounced reduction in respiration frequency over time, dropping from 35 times on Day 0 to only 2 times on Day 7, indicating a significant slowdown in metabolic activity. In contrast, Sample B showed no recorded respiration on Day 6 and Day 7, suggesting a potential stabilization or dormancy in metabolic processes during these periods. Sample C, while exhibiting a similar rapid increase in respiration initially, showcased a more gradual reduction in respiration frequency, declining to 4 times on Day 6 and no respiration on Day 7, potentially indicating a different metabolic response or adaptation.

The observed differences in respiration patterns among the samples can be linked to the variations in perforation sizes and sample weights. Sample A, with the smallest perforation size (L=455.312um, A=12286.768um2) and slightly lower weight (75.34 g), exhibited a significant reduction in respiration frequency over time, potentially indicating that the smaller perforation size limited oxygen exchange and led to reduced metabolic activity. On the other hand, Sample B, with a larger perforation size (L=491.090um, A=14725.077um2) and slightly lower weight (74.81 g), displayed no recorded respiration on Day 6 and Day 7, suggesting a possible stabilization or dormancy possibly due to better oxygen availability facilitated by the larger perforation size. Sample C, with the largest perforation size (L=522.96um, A=15883.342um2) and slightly higher weight (75.47 g), exhibited a gradual reduction in respiration frequency, potentially indicating a more prolonged metabolic activity likely supported by the enhanced oxygen exchange facilitated by the larger perforation size.

Overall, while all samples showed increasing respiration rates over time, the larger perforation sizes correlated with more rapid initial increases and eventual stabilization or reduction in respiration, highlighting the influence of micro-perforation size on fresh-cut apple respiration dynamics.

5.4 Discussion

This study aimed to evaluate the respiration rate as well as potential gas change measurement of fresh-cut apple fruits during postharvest storage. This study compared the respiration rates of three different fresh-cut apple samples, denoted as Sample A, Sample B, and Sample C, and shed light on the significant relationship between micro-perforation sizes, sample weights, storage conditions, and resulting metabolic activities.

Sample A which is characterized by the smallest micro-perforation size and a slightly lower weight, exhibited a substantial reduction in respiration frequency over time. This reduction can be attributed to the limited oxygen exchange most likely facilitated by the smaller perforation size which led to reduced metabolic activity as supported by the findings of two studies (Al-Ati & Hotchkiss, 2002; Hussein, Caleb, Jacobs, et al., 2015). Reduced metabolic activity has been associated with a high potential to prolong the shelf life of fresh-cut fruits as indicated by findings of several studies (Ghidelli & Pérez-Gago, 2018b; Iturralde-García et al., 2022; R. C. Soliva-Fortuny & Martín-Belloso, 2003). The decrease in respiration rates observed in Sample B which had a larger perforation size but slightly lower weight, particularly on Days 6 and 7, suggests a possible stabilization or dormancy phase likely due to better oxygen availability without compromising the integrity of the packaging as suggested by findings of a study (Brody et al., 2010). On the other hand, Sample C having the largest perforation size and a slightly higher weight, displayed a more prolonged metabolic activity, potentially supported by enhanced oxygen exchange which may have been facilitated by the larger perforation size aligning with the previous research statement (Wilson et al., 2019). However, studies have shown that larger perforation sizes in the MAP of fresh-cut fruits could negatively impact the product's shelf life and overall quality (Owoyemi et al., 2021; Wilson et al., 2019). Nevertheless, the subsequent stabilization or decline in respiration rates across all samples suggests a balance between oxygen availability and metabolic demand.

The observed trends in respiration rates across the samples corroborate findings from previous studies on modified atmosphere packaging (MAP) and controlled atmosphere storage (CAS) of fresh-cut apples. A study (Mangaraj & Goswami, 2008) that determined the respiration rate of fresh-cut apples stored at 5ºC using mathematical models also recorded a steady increase in the oxygen concentration of the apples as the study duration progressed to 150 hours aligning closely with the findings of this study. The study (Mangaraj & Goswami, 2008) also recorded a similar R^2 coefficient of 0.997. Another study (Fagundes et al., 2013) which determined the respiration rate of fresh-cut apples using gas chromatography also found results that align with those of this study. This study found that the oxygen concentration increased steadily throughout the 190 hours of storage at 5ºC and also recorded a similar R^2 coefficient of 0.896. It is worth noting that although these studies (Fagundes et al., 2013; Mangaraj & Goswami, 2008) used a different method for data collection and analysis, the results still aligned closely with that of this study and this implies that, to a large extent, temperature and time are the major determinants of respiration rate in fresh-cut apples.

Furthermore, the findings of this study align with existing literature which found that variations in packaging parameters, such as perforation sizes and gas composition, significantly influence respiration rates fresh-cut apples (Al-Ati & Hotchkiss, 2002; Belay et al., 2016; Cliff, Toivonen, Forney, & Lu, 2010; Hussein, Caleb, Jacobs, et al., 2015). This study's finding further aligns with principles of gas diffusion and respiration kinetics elucidated by some studies, where optimal gas exchange promotes metabolic processes while minimizing anaerobic conditions that could lead to physiological disorders (Izumi et al., 2016; Qadri et al., 2016; Saltveit, 2020).

Additionally, the observed trends in respiration rates across the samples highlight the dynamic nature of metabolic processes in fresh-cut apples during storage. The initial burst of respiration activity followed by a steady phase and, in some cases, a plateau or dormancy phase reflects the complex relationship between physiological responses and environmental factors like temperature and gas composition within the packaging, a concept that is supported by the findings of several literature (Belay et al., 2019; Cortellino et al., 2015; Fagundes et al., 2013; Predrag & Danijela, 2017; Putnik et al., 2017). Also, the cessation or reduction in respiration rates observed in some samples, particularly on Days 6 and 7, raises intriguing questions about metabolic stabilization and dormancy phenomena. These periods could signify adaptive responses of apple tissues to environmental cues and storage conditions, a phenomenon that has been highlighted by existing research (Brizzolara et al., 2019; Cukrov et al., 2016). Interestingly, no existing study has been able to contrast the findings noted above which strengthens the notion that temperature, packaging, storage conditions, and gas compositions directly influence the respiration rate of fresh-cut apples.

While the study primarily focuses on packaging parameters, it is crucial to consider the broader environmental context, including temperature variations and gas compositions within storage environments. Research has emphasized the correlation between these factors and respiration rates in fresh-cut apples (Belay et al., 2019; Cortellino et al., 2015; Fagundes et al., 2013; Predrag & Danijela, 2017; Putnik et al., 2017). Additionally, the observed trends in respiration rates across the samples, especially in terms of the initial rapid increases to potential stabilization or decline, reflect the complex responses of apples to storage conditions and gas environments, a concept highlighted in the findings of some studies (Brizzolara et al., 2019; Li, Zheng, et al., 2022; Wright et al., 2015). Furthermore, the storage temperature of 5°C, as mentioned in the study, is crucial in modulating enzymatic activity and metabolic rates. Lower temperatures generally slow down enzymatic reactions, including respiration processes, contributing to the extended shelf life of fresh fruits as evidenced by several study findings (Adhikary et al., 2021; Banin Sogvar et al., 2020; Brizzolara et al., 2020; Li, Zhao, et al., 2022). Also, the observed trends in respiration rates across the samples reflect these temperature-dependent metabolic responses and agree with the findings of two studies (Fagundes et al., 2013; Mangaraj & Goswami, 2008). However, further investigations into temperature gradients within the packaging and their impact on localized respiration dynamics of fresh-cut apples could provide deeper insights.

Additionally, the R^2 coefficients obtained for each sample (0.9233, 0.889, and 0.992 for Sample A, Sample B, and Sample C, respectively) indicate strong correlations between storage duration and respiration rates. These coefficients are consistent with predictive models proposed by studies that highlight the predictive power of storage time in determining postharvest physiological changes (Ghosh & Dash, 2018; R. Singh et al., 2014; Sousa et al., 2017). These models, often based on Arrhenius equations or modified kinetic models, integrate temperature effects, gas concentrations, storage conditions, and fruit characteristics to forecast respiration dynamics accurately (Caleb et al., 2018; Mahajan & Caleb, 2017). This study's R^2 values validate the applicability of such models in fresh-cut apple storage management. The high R^2 values noted in this study indicate a robust relationship between time and respiration rate which can enable researchers and industry practitioners to develop predictive models for optimizing storage conditions and shelf-life management. Also, these coefficients emphasize the critical role of storage time in influencing metabolic activities, further supporting the need for optimized packaging strategies to prolong shelf life while maintaining product quality.

Furthermore, this study's integration of advanced equipment such as oxygen gas checkers, laser perforators, oxygen gas sealers, and digital microscopy showcases the importance of technological advancements in postharvest research. This aligns with the trend seen in recent literature (Barkov, 2023; Eswaran et al., 2024) which has been directed towards leveraging cutting-edge tools for precise data collection and analysis, thereby enhancing the reliability and accuracy of experimental results in relation to fruit respiration rate. Moreover, the detailed sample preparation and packaging methods outlined in the study methodology reflect the importance of precision and control in experimental design and go a long way in ensuring reliable results. Overall, the use of advanced equipment like the oxygen gas checker and laser perforator machine, coupled with meticulous monitoring using digital microscopy, reflects best practices in experimental setup and data collection. This aligns with the industry's growing emphasis on technological innovations for postharvest handling (Fernandez et al., 2021; Palumbo et al., 2022), ensuring optimal product quality and safety.

In conclusion, the study's findings contribute valuable insights into the impact of micro-perforation sizes, sample weights, temperature, time, gas composition, and packaging method on the respiration rate of fresh-cut apples.

5.5 Implication for Practice and Future Research

The findings of this study have direct implications for postharvest practices in relation to fruit respiration as well as further research in the area of postharvest physiology of fresh-cut fruits and how these fruits respond to different atmospheric and storage conditions.

Firstly, the observed variations in respiration rates highlight the importance of tailoring packaging solutions to specific fruit characteristics. For practitioners in the food industry, it is important to note that optimizing micro-perforation sizes based on fruit type, weight, storage condition, and desired shelf life can lead to improved product quality and extended freshness. This customization can minimize respiratory losses and enhance overall marketability. Additionally, based on the role the storage conditions played in the respiration rate of the apples, understanding the impact of storage conditions, such as temperature and gas composition, will be crucial for developing effective packaging strategies that maintain product integrity throughout the supply chain.

From a sustainability perspective, the study encourages the development of eco-friendly packaging solutions that balance product protection with environmental conditions. Future research and industry initiatives can focus on designing recyclable and biodegradable materials with optimized gas permeability properties. Additionally, the study's insights into the relationship between packaging design and respiration kinetics provide a foundation for exploring novel materials and production techniques that align with circular economy principles.

Furthermore, the study emphasizes the significance of advanced analytical techniques in quality assurance and process optimization, such as oxygen gas checkers and laser perforators. For those in the food industry, integrating these technologies into packaging processes can enhance precision and support sustainable packaging practices that will guarantee the increased quality of the product.

Building upon the findings of this study, future research can explore additional factors influencing respiration dynamics in fresh-cut apples and fruits in general. For example, investigating how postharvest treatments like modified atmosphere packaging (MAP) or micro-perforation improve the storage quality of fresh-cut fruits can provide further insights into extending shelf life and preserving product quality. Moreover, studying the correlation between genetic factors, fruit maturity, and storage conditions can enhance the understanding of metabolic pathways and physiological responses in fresh-cut apples. Finally, research on advances in analytical techniques, including non-destructive imaging methods and metabolomics analyses can be embarked on as the findings have the potential to offer opportunities to research deeper into postharvest physiology and metabolic regulation of fresh-cut fruits.

5.6 Strengths and Limitations of the Study

Based on the methodology used in this study, it can be said that the study benefits from the controlled experimental conditions, including consistent storage temperatures and standardized packaging procedures. This enhances the reliability and reproducibility of the results, allowing for meaningful comparisons between different samples as highlighted by research (Von Kortzfleisch et al., 2020). Furthermore, the use of advanced analytical tools such as oxygen gas checkers, laser perforators, and digital microscopes contributes to the accuracy and precision of data collection according to studies. Research has shown that these technologies enable real-time monitoring and detailed analysis of respiration dynamics and packaging characteristics (Massaroni et al., 2019; Vega-Diez et al., 2024). Additionally, the study incorporates comprehensive data collection methods, including mean oxygen differences, standard deviations, and mean deviations over time as well as the application of statistical analysis, including R^2 coefficients and graphical models. This multi-dimensional approach provides a comprehensive understanding of respiration kinetics and variability among samples as supported by studies (Belay et al., 2016, 2019). Other studies (Hair et al., 2021; van de Schoot et al., 2021) have also shown that statistical techniques enhance the interpretation of relationships between variables and validate the significance of observed trends.

Despite the numerous strengths of the study elucidated above, the study was also limited by various factors. Firstly, the study's small sample size, while adequate for experimental purposes, may limit the generalizability of findings to broader populations or commercial-scale operations as posited by existing literature (Lakens, 2022). Also, the study focuses on a relatively short-term storage period of seven days, which may not fully capture long-term respiration dynamics or extended shelf-life considerations. Furthermore, while the study examines the impact of micro-perforation sizes on respiration rates, other potential variability factors such as humidity levels, light exposure, packaging material, and postharvest treatments are not explicitly addressed. Finally, the study's controlled environmental conditions, while it may have been beneficial for experimental control, may not fully replicate real-world storage environments with fluctuating temperatures, atmospheric conditions, and storage practices.

In summary, the strengths of the study lie in its controlled experimental design, advanced technological tools, comprehensive data collection, and statistical analysis. However, addressing limitations related to sample size, generalizability, long-term storage effects, consideration of additional variables, and environmental realism can further enhance the reliability of the study’s findings and its applicability to real-world scenarios.

6.0 SUMMARY

6.1 Conclusion

This study aimed to evaluate the respiration rate as well as potential gas change measurement of fresh-cut apple fruits during postharvest storage and after the study duration of 7 days, the following key findings were noted: Oxygen concentration increased steadily throughout the study duration, with rapid increases observed on Day 0 and Day 1 across all samples. Sample A showed a pronounced reduction in respiration frequency, recording only 2 instances of respiration by Day 7. Sample B displayed no recorded respiration on Day 6 and Day 7, suggesting a potential stabilization or dormancy in metabolic processes. Sample C exhibited a gradual reduction in respiration frequency, indicating a more prolonged metabolic activity before cessation of respiration by Day 6.

Furthermore, the study showed that micro-perforation hole sizes influenced respiration kinetics, with smaller perforation sizes potentially limiting oxygen exchange and reducing metabolic activity. Larger perforation sizes facilitated enhanced oxygen exchange, supporting prolonged metabolic activity before the eventual cessation of respiration.

The findings of this study have highlighted significant correlations between time and respiration rate, showcasing a strong linear relationship as evidenced by high R^2 coefficients across the samples. The respiration rate of fresh-cut apples consistently increased over the study duration, with notable rapid increases in the initial days. However, a key observation was the gradual reduction in respiration frequency over time, leading to a complete cessation of respiration in some samples before the end of the 7-day study period. These findings have substantial implications for practice, particularly regarding the optimization of packaging techniques for fresh-cut fruits to prolong shelf life and maintain product quality. Furthermore, for future research, these results emphasize the importance of exploring additional factors that may influence respiration dynamics in fresh produce, paving the way for more targeted interventions and improved postharvest management strategies.

6.2 Recommendations

Based on the key findings of these studies, the following recommendations will be beneficial for industry stakeholders and future researchers about extending the shelf-life of fresh-cut apples under postharvest storage:

1) Conduct further research to determine the optimal micro-perforation size and pattern that balances oxygen exchange for metabolic activity while also minimizing respiration losses in fresh-cut apples.
2) Explore innovative packaging solutions such as active and smart packaging to create environments that can dynamically adjust oxygen levels based on real-time respiration rates, thereby extending the shelf life of fresh-cut fruits.
3) Develop and integrate Internet of Things (IoT) sensors within packaging to monitor and transmit data on respiration rates which will allow for remote monitoring and timely interventions.
4) Expand studies to investigate the combined effects of factors like temperature, humidity, gas composition, storage container, and packaging technique on respiration rates to develop comprehensive models for postharvest management of apple fruits.
5) Extend the study duration to investigate the long-term effects of storage on respiration rates including potential dormancy periods or shifts in metabolic activity over extended storage periods.
6) Explore eco-friendly packaging materials and technologies that reduce environmental impact while maintaining optimal storage conditions for fresh-cut fruits.

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APPENDICES

Appendix 1: Full Citation List of Numbered References on Respiratory Kinetic Model Table

Reference Number	**Citation**
7	(Singh et al., 2014)
16	(Del Nobile et al., 2006)
25	(De Bonis et al., 2013)
55	(Sousa et al., 2017)
58	(Ghosh & Dash, 2018)
64	(Barrios, Lema, & Lareo, 2014)
72	(Dash et al., 2009)
74	(Rocculi et al., 2006)
75	(Heydari et al., 2012)
76	(Wang et al., 2009)
77	(Barrios, Lema, & Marra, 2014)

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Declaration

Me, as the undersigned **Abdul Umaro Tholley – T6X9JM** declares, that the Diploma Thesis entitled Study of Apple fruit respiration under special conditions.

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