

PHYSIOCHEMICAL QUALITY, INSTRUMENTAL AND SENSORY
EVALUATION OF APPLES TREATED BY POST-HARVEST TREATMENT
TECHNOLOGIES: DYNAMIC CONTROLLED ATMOSPHERE(DCA),
CONTROLLED ATMOSPHERE(CA), AND 1-METHYLCYCLOPROPENE (1-
MCP)

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ABSTRACT

In recent years the apple industry has been in a state of hypercompetition, which is defined as escalating competition based on price-quality positioning. Poor apple quality can result in alienation, decreasing demand, and loss of sales as consumers respond by changing purchasing behaviors. In addition, countries such as England, New Zealand and the United States have established legal standards for the edible quality of apple. The inability to achieve these requirements normally led to product downgrade or even complete loss of the product. One of the key post-harvest factors that can adversely impact the quality and shelf-life of apples is the storage condition. Controlled atmosphere (CA), application of 1-methylcyclopropene (1-MCP), and dynamic controlled atmosphere (DCA) are available methods to help extend the storage period or preserve perceived quality of apples. However, each method has its own influence on apple quality attributes in terms of appearance, aroma, taste, and texture. The objective of this project was to provide a review of how dynamic controlled atmosphere (DCA), controlled atmosphere (CA), and the application of 1-Methylcyclopropene impact the physicochemical, instrumental, and sensory quality of apples. Based on a literature review and a sensory test after 6month of storage apples, it was noticed that DCA provided a better result in preventing water core and internal browning than CA and CA+1MCP. CA stored apples generally received the lowest flesh firmness among the three methods. DCA and CA+1MCP showed similar sensory results in overall liking, texture liking, aroma liking based on the sensory evaluation. As the demand for organic apples increasing, DCA can become a potential replacement for CA+1-MCP for achieving similar hedonic results and maintaining equivalent or even better-quality results than CA. However, when selecting proper storage, it is still critical to take consideration of the types of cultivars, as different cultivars respond differently towards the three treatments.

BIOGRAPHICAL SKETCH

Menghan Shi completed her bachelor's degrees from the Ohio State University, with double majors in Food Science and Business Administration. During her time at the Ohio State University, she was a member of the Scholar Program and finished her Food Science bachelor's degree with a research distinction. Thereafter, she joined Cargill and Bowman Andros Products, LLC focusing on food safety and food quality.

In 2020 Spring, Menghan joined Dr. Robin Dando's lab in the Food Science Department at Cornell University. During the study, her project and study concentration was on sensory and consumer science. Upon graduation she plans to bring back the knowledge to industry for future development and growth.

To my family for all their support, patience, and love

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CHAPTER 1: INTRODUCTION

The apple industry has been experienced intense competition for a number of years, with apples representing one of the most commonly consumed fresh fruits in the US and globally, with a huge global market consumption of 75.8 million tons per year, including 41.0 million tons in China, 11.5 million tons in EU, and 4.8million tons in the USA. (USDA, 2020). Some economists described the apple industry as in a state of hypercompetition, which, by definition from D' Aveni and Gunther (1994), involves rapidly escalating competition based on price-quality positioning (Harker et al., 2003). With this in mind, research is vital to better understand consumers' perspectives on the various apple cultivars, to evaluate the key sensory characteristics that lead to consumer satisfaction, to segregate consumers by groups with unique sensory preferences, and, ultimately, to provide valuable information that supports production and marketing strategies in this highly competitive market.

Some of this research is devoted to investigating novel post-harvest storage technologies with the goals of maintaining the quality of apples, ensuring food safety, and therefore reducing post-harvest losses. Among all the food lost or wasted globally every year, about 20-40% of all fruits and vegetables in developing countries, and 10-15% in developed countries are lost during the post-harvest stages (Gustavsson, 2011). Apple, as a highly perishable fruit, is susceptible to long-term storage disorders. Even though long-term cold storage at 0°C is commonly used to slow down apple respiration and ethylene biosynthesis, thus delaying ripening, this can still lead to other physiological disorders, such as superficial scald, water core and internal browning (Lurie & Watkins, 2012). Moreover, physicochemical properties such as firmness, pigmentation, color, total soluble solids (TSS) and total acidity (TA) can also be changed during the process of long-term storage to impact the perceived sensory quality of apples, thus influencing consumer satisfaction (Mditshwa et al., 2018).

1.1 Post-Harvest Treatments: 1-MCP, CA and DCA:

Chemical and physical treatments are two major ways to slow down ripening, controlling physiological disorders, extending the storability of apples, and maintaining apple quality. In post-harvest storage, ethylene is generated during undesirable ripening processes. It leads to soften apples that negatively impact consumer acceptability, as a soft apple is often also perceived as less juicy, crisp, crunchy, or more mealy than firmer ones (Harker, Maindonald, et al., 2002; Harker, Marsh, et al., 2002).

1-methylcyclopropene (1-MCP) is a synthetic cyclic olefin that controls ripening and physiological disorders by delaying respiration and repressing ethylene production along with other harmful volatiles that can negatively impact the quality of stored apples, such as alpha-farnesene, conjugated trienols and 6-methyl-5-hepten-2-one (Jung & Watkins, 2009). 1-MCP can work at a very low concentration as an ethylene competitor to bind and block ethylene's access to the fruit's ethylene-binding receptors due to its affinity for the ethylene receptor at 10 times greater than that of ethylene (Sisler & Serek, 1997). With increasing storage period, 1-MCP treatment is also applied in combination with other physical treatments, such as Controlled Atmosphere (Thompson & Bishop, 2016). It was suggested that using two or more times as much 1-MCP prior to and post of CA storage can change the apple's texture due to delaying the softening of apple flesh (DeEll et al., 2016).

In the last decades, increased efforts to adopt physical instead of chemical treatments have become more widespread, due to rapid surged concern of non-environmentally friendly impact and demand for organic food. Static controlled atmosphere (CA; >1% oxygen (v/v)), ultra-low oxygen (ULO; <1% oxygen (v/v)) and dynamic controlled atmosphere (DCA) are the three major physical postharvest technology for the storage

of apples (Mditshwa et al., 2018). Controlled atmosphere (CA) and Dynamic controlled atmosphere (DCA) are known for reducing respiration rate, decreasing ethylene production, controlling physiological disorders, and reducing the incidence of off-flavors. (Mditshwa et al., 2018; Weber et al., 2015; Wright et al., 2015). DCA is a relatively newer technology in comparison with controlled atmosphere (CA) and ultra-low oxygen (ULO) and has recently received higher attention in horticulture and postharvest research. There are overall three major types of DCA technology: Chlorophyll fluorescence (DCA-CF), Respiration quotient (DCA-RQ), and Ethanol sensor (DCA-ET). CA is thought to be less effective than DCA in controlling certain physiological disorders such as internal browning and CO₂ injury (Mditshwa et al., 2018). Moreover, (Kittemann et al., 2015) suggested that DCA can achieve lower weight loss during a 7-month storage, while reducing energy consumption by 20% when compared to ULO by increasing storage temperature from 1°C for ULO to 5°C for DCA.

1.2 Apple quality

Physiological Quality

Selection of post-harvest storage technologies can positively or negatively impact the development of physiological disorders, such as water core, internal browning, core flush, and superficial scald; ultimately, proper post-harvest treatment can significantly improve the apple postharvest quality and reduce fruit waste due to quality rejection at fruit processing and commercial trades ((Mditshwa et al., 2018)

Water core is a common and cultivar-dependent disorder, which typically leads to the development of translucent water-soaked appearance around the vascular bundles of coreline or fruit core and an accumulation of sorbitol in the intercellular spaces (Ferguson et al., 1999; Saquet, 2020). Serious breakdown of tissue from water core can lead to potential loss, off-flavor development, lower acceptance in the marketplace or downgrade of the product (Neuwald et al., 2012; Saquet, 2020). This disorder is often found in physiologically mature pre-harvested apples and can decrease or even

disappear entirely depending on its severity during post-harvest storage (Ferguson et al., 1999; Saquet, 2020). (Yamada et al., 2006) reported a higher incidence of early water core during summer in warmer regions of Japan, and suggested a positive correlation between fruit temperature and water core intensity before harvest.

It is essential to understand that this disorder can serve as a precursor of other permanent injuries or disorders, such as flesh browning and internal breakdown during and after storage (Saquet, 2020). Fuji apples, which generally harvested at advanced maturity, is one of the cultivars more susceptible to water core and flesh browning (Kweon et al., 2013) and it is common for apple with high initial water core levels to be stored for a longer period to allow the water core to dissipate before apples are sold in the markets (Neuwald et al., 2012). As a higher level of initial water core incidence can disappear during storage and transform into an internal browning disorder (Köpcke, 2015), it becomes critical for considering the right harvest time and selecting proper storage conditions to balance out these two disorders.

CA storage condition with 1.5kPa O₂, <1kPa CO₂ was reported to reduce water core disorder in Fuji apples quicker than a higher CO₂ level (2.5kPa); furthermore, the flesh browning also increased as the CO₂ level increased from <1kPa to 1.5 kPa (Kweon et al., 2013). Similarly, (Gonzalez et al., 2001) also suggested that higher CO₂ concentration (18% CO₂ at 20°C) is closely related to CA-induced internal browning during a 12 weeks study. (Streif & Saquet, 2003) suggested Elstar apples were more damaged in higher CO₂ and higher O₂ CA storage. Braeburn is another very popular apple cultivar, which ranked 5th in the Austrian apple production. Similar to Fuji, it is also more susceptible to internal browning under CA conditions, especially when exposed to high O₂ levels (Lafer, 2008). Even though storage condition plays a critical role in the development of internal browning disorder, such occurrence is extremely complicated and can also be induced by other pre-harvest conditions, such as harvest date (Lafer, 2008), crop load, or nutritional composition of

fruits (Lafer, 2008)). A late harvest date can substantially promote internal browning disorders compared with early or optimally harvested fruit (Lafer, 2008). Using a delayed CA-storage, with the optimum duration of CA-delay of 30 days, can significantly reduce flesh browning (Streif & Saquet, 2003).

In addition to CO₂-level, storage temperature is another key factor that impacts the dissipation rate of the water core and internal browning during storage. (Köpcke, 2015) reported very minimal internal browning and water core disorders at $\leq 10^{\circ}\text{C}$, suggesting that higher temperature facilitated the dissipation of water core in ‘Gloster’ apples and decreased the internal browning incidence.

Superficial scald is another important physiological disorder that is generally reported by apple quality researchers (Çalhan et al., 2016; Lurie & Watkins, 2012; Mditshwa et al., 2018; Zanella et al., 2005). This disorder is commonly seen in post-harvest apples and pears. Superficial scald manifested as brown or black patches on the surface layers of fruit skins and it is generally associated with long periods of low-temperature storage (Lurie & Watkins, 2012). The majority of the research related to this disorder has been carried out with “Granny Smith” because the disorder is easy to be identified for green apples and this cultivar is highly susceptible to superficial scald (Çalhan et al., 2016; Lurie & Watkins, 2012). Other susceptible cultivars include Red Delicious, Cripps Pink, Stayman Winesap, Morgenduft, and Jonagold (Zanella et al., 2005). In the past, antioxidant diphenylamine (DPA) was generally used to treat apples for protection, but increasing concerns of chemical treatment and its pollutant or health-hazardous nature have encouraged alternative strategies (Tomic et al., 2016; Zanella et al., 2005). 1-MCP treated Granny Smith was reported with no scald after 9 months of cold storage, while DPA exhibited greater susceptibility after 6 and 9 months of storage than 1-MCP, suggesting 1-MCP as more effective (Tomic et al., 2016). For non-chemical alternatives, (Çalhan et al., 2016) compared the effects of the regular atmosphere (RA), CA, and DCA and 1-MCP treatment on superficial scald of

“Granny Smith”, concluding that DCA, CA, and CA+1MCP treatments all can effectively prevent superficial scald disorder. Furthermore, DCA was reported by (Zanella et al., 2005) successfully demonstrated a significantly better effect than the CA condition and had an equivalent scald prevention effect as 1-MCP treatment or DPA treatment.

Instrumental measurement and sensory quality

In addition to maintaining the physiological quality of apples during storage, sensory quality is another key parameter that will largely impact consumer purchasing decisions. Past sensory experience can substantially influence consumers’ expectations and judgment about apple quality for their future purchases (Harker, Maindonald, et al., 2002). For a single fruit-type or cultivar, consumer preferences are often defined by the ripeness stage (Harker et al., 2003) and the ripeness stage is closely related to storage time and storage treatment. Recent research has documented that ripening regulation as affected by DCA and 1-MCP application showed positive impact in maintaining fruit texture, soluble solids, and acidity but suffered from insufficient aroma formation (Streif et al., 2010).

Consumer sensory studies generally are more expensive and less accessible than instrumental measurements, so fruit quality and sensory attributes, such as texture, sweetness, acidity, are commonly assessed through instrumental measurements. The puncture test using penetrometer or firmness tester has been widely used in industry and academia, with 28 out of 44 pipfruit research papers adopting penetrometers to assess fruit texture (Harker, Maindonald, et al., 2002). Other generally used instrumental assessments for apple quality are the measurement of °Brix or soluble solids concentration, and titratable acidity (Çalhan et al., 2016; Harker, Maindonald, et al., 2002; Harker, Marsh, et al., 2002; Köpcke, 2015; Kweon et al., 2013). Texture

attributes, such as hardness and crispness, and flavor attributes, such as sweetness and sourness, are essential to consumer preference. Consumer segmentation was reported to be according to whether a juicy, acidic apple or a sweet, hard apple was preferred (Dailliant-Spinnler et al., 1996).

Despite the foundation focuses on the physiological and instrumental measurement of apple quality from previous research, there has been limited work that thoroughly reviews the questions 1) can consumers detect a difference in sensory quality in apples when compare DCA, CA and CA+1MCP, 2) if detectable, how do storage technologies impact consumer perception across apple cultivars, and 3) are there similar trends of impact on quality, sensory characteristics, and consumer preferences observed among different storage technologies? Understanding these questions can help to provide insight to the apple industry in making decisions during selecting proper storage design, to better balance sensory quality improvement goals with post-harvest storage management investment.

CHAPTER 2: MATERIALS AND METHDOS

2.1 Literature Review

An electronic search was conducted on Web of Science and Google scholar databases following the PRISMA principles (Moher et al., 2015) using the following searching strategy:

- 1- (apple* OR "pome fruit*")
AND ("controlled atmosphere" OR DCA OR 1-MCP OR "1-Methylcyclopropene" OR "storage method*")
AND ("sensory analys*" OR "sensory qualit*" OR "sensory evaluation" OR "sensory characteristic*" OR Texture OR aroma OR appearance OR taste)
- 2- (apple* OR "pomefruit*") AND
(DCA OR DCA-RQ OR DCA-CF) AND
("sensory analys*" OR "sensory qualit*" OR "qualit*" OR "sensory evaluation" OR "sensory characteristic*" OR Texture OR aroma OR appearance OR taste OR hedonic OR "descriptive analys*" OR "preference*" OR "acceptabilit*")
- 3- (apple* OR "pomefruit*") AND
(DCA OR DCA-RQ OR DCA-CF OR "dynamic controlled atmosphere")AND
(CA OR "controlled atmosphere" OR "CA+1-MCP")AND
(1-MCP OR "1-Methylcyclopropene")AND
("sensory analys*" OR "sensory qualit*" OR "sensory evaluation" OR "sensory characteristic*" OR Texture OR aroma OR appearance OR taste OR hedonic OR "descriptive analys*" OR "preference*" OR "acceptabilit*")

After the initial search, papers were then screen through title and abstract based on its suitability to this research: 1) must contain DCA technology 2) provided primary focus on the sensory quality comparison at least between two of the following treatments: DCA, CA, CA+1MCP 2) provided a supplementary physiological quality between two of the following treatments: DCA, CA,

CA+1MCP,3) provided a supplementary instrumental quality comparison between two of the following treatments: DCA, CA, CA+1MCP 4) must be whole apples

2.2 Apples and Sensory Evaluation Test

Due to the limited research papers found that focused on sensory quality comparison among the three technologies, consumer testing was conducted at the Cornell Sensory Testing center with the following procedure:

2.2.1 Samples and Storage Methods

Four commonly consumed apple cultivars (Honeycrisp, Golden Delicious, Jonagold, and Fuji) were tested with sensory evaluation. Honeycrisp was harvested on September 18th, 2020, Golden Delicious on October 7th, 2020, Jonagold on October 13th, 2020, and Fuji on October 20th, 2020. Apples were grown and harvested locally (Ithaca, NY) by collaborators at the School of Integrative Plant Science at Cornell University.

All harvested apples were placed into storage for six months with three different treatments applied to each type of apple cultivar: dynamic controlled atmosphere based on chlorophyll fluorescence (DCA-CF), controlled atmosphere, and controlled atmosphere with 1-MCP application. After the 6month storage removal, apples were placed for 1-3 days waiting for the sensory evaluations. A schedule for harvest and sensory testing for each cultivar and their storage condition was shown in the Table 1.

Harvest Time	Testing Time	Cultivar	Storage temperature	Regime condition
09/18/2020	Session 1: 03/23/2021-03/25/2021	Honeycrisp	3°C after 1 week at 10°C	CA: 2% O ₂ / 1% CO ₂ , CA+1MCP DCA-CF: 0.7 % O ₂ / 1% CO ₂
10/07/2020	Session 2: 4/13/2021-4/15/2021	Golden Delicious	0.5°C	
10/13/2020	Session 3: 4/20/2021-4/22/2021	Jonagold	0.5°C	
10/20/2020	Session 4: 4/27/2021-4/29/2021	Fuji	0.5°C	

Table1. Apple harvest and testing schedule for three different storage treatments

2.2.2 Panelists and Sensory Evaluation test

All procedures of the study relating to human subject research were reviewed and approved by the Cornell University Institutional Review Board for Human Participant Research (IRB). Panelists were recruited through Cornell Sensory Evaluation Center, via a series of mailing lists, advertising flyers posted on campus or during walk-in. All panelists were prescreened with Covid-19 Attestation form to ensure healthy body temperature and proper facility access authorization and provided informed consent. Four sensory sessions (Table 1.) were conducted: eighty-one panelists for the Honeycrisp session, eighty-four panelists for the Golden Delicious session, eighty-three panelists for the Jonagold session, and eighty panelists for the Fuji session. All panelists were between the age of eighteen to sixty-eight.

Each session lasted around 15-20 minutes, and each panelist was provided with a value of \$5 cash compensation for each session. During each session, one sample bag along with testing instruction was provided to each panelist and the panelists were instructed to follow the questionnaire link on the instruction sheet to complete the

questions on iPad (Apple Inc, Cupertino, CA) through Red Jade sensory evaluation software (Curion, Deerfield, IL) in an individual testing room.

In each session, panelists evaluated three slices of fresh-cut samples from three storage treatments of a single apple cultivar. Samples were served in small plastic containers marked with 3-digit codes, presented in counterbalanced order with a monadic sequential design. Same questionnaire was used across all the sessions and the only modification across different sessions was when panelists evaluated apples' appearance. Sample photos were taken for the corresponding session by randomly selecting apples for each treatment. Overall liking and major apple sensory characteristics were evaluated on the nine-point hedonic scale and JAR scale. A list of questionnaire summary was provided in Table 2. Demographic and purchasing behavior-related questions were asked at the end of each session.

Sensory Parameters	Scale type	Scale range
Appearance	Nine-point hedonic	Like it extremely--dislike it extremely
Appearance color	JAR	Much too yellow—Much too green
Overall Liking	Nine-point hedonic	Like it extremely--dislike it extremely
Aroma	Nine-point hedonic	Like it extremely--dislike it extremely
Flavor	Nine-point hedonic	Like it extremely--dislike it extremely
Texture	Nine-point hedonic	Like it extremely--dislike it extremely
Color of apple flesh	JAR	Much too light ---Much too Dark
Texture of apple flesh	JAR	Much too soft ---Much too hard
Skin Toughness	JAR	Not at all tough enough – Much too Tough
Crispness	JAR	Not at all crisp enough --- Much too Crisp
Juiciness	JAR	Not at all juicy enough – Much too Juicy

Sweetness	JAR	Not at all sweet enough – Much too Sweet
Sourness	JAR	Not at all sour enough – Much too Sour
Notice of aftertaste	Y/N	If yes, word description of aftertaste

Table2. Summary of apple sensory questionnaires for evaluated sensory parameters

2.2.3 Data analysis

Data from nine-point hedonic scale were analyzed with a linear mixed model in SPSS (IBM, Corp, Armonk, NY), using a statistical significance value of $p < 0.05$, and the model was modified with Estimate Marginal (EM) means syntax to provide a pairwise comparison, using least significant difference adjustment and Bonferroni correction. The panelist was selected as a random effect, with fixed effects for analysis based on the cultivar (4 levels: Honeycrisp, Golden Delicious, Jonagold, and Fuji), treatment (3levels: CA, DCA, CA+1MCP), and cultivar * treatment interaction. The interaction between cultivar and treatment was evaluated in the model (nine-point scale liking scores = cultivar + treatment + cultivar * treatment). Data were visualized by SPSS.

JAR scale data were treated as categorical data and analyzed using XLStat penalty analysis (Addinsoft, NewYork, USA). For each sensory characteristic, JAR data were grouped into three categories, specifying the mean drops for “not enough” level and “too much” level and a zero-mean drop for “just about right” level. Visualization of data with spider plot was created using the weighted mean drop value, which was calculated by taking the product of mean drop value and the percent of the panelists.

CHAPTER 3: RESULT AND DISCUSSION

3.1 Literature Review Results:

Based on the search strategy one, two, and three, a total of 345, 70 and 22 results were found, respectively. After screening, a total of 16 papers that fitted the screening criteria were reviewed and summarized. Conclusions about the quality levels for quality measurements (physiological disorder, instrumental, and sensory attributes) were manually and qualitatively categorized into three levels from 1 to 3 (1 as the highest to 3 as the lowest). The decision was made based on the following criteria:

- 1- Highest quality: the tested quality attributes ranked the best among the evaluated treatments, or the tested quality attributes maintained or deviated their quality standard in comparison with their desired quality insignificantly.
- 2- Middle Quality: the tested quality attributes ranked in the middle, or the tested quality attributes were lower than the Highest quality either significantly or insignificantly.
- 3- Lowest Quality: the tested quality attribute ranked the least, or the tested quality attributes were significantly or insignificantly lower than the middle quality.

A summary of the quality levels for various quality attributes was provided in Figure 1. Majorities of the previous research focused on the physiological disorder and instrumental measurements of the quality attributes. Only limited researchers conducted sensory tests to evaluate sensory quality attributes (Aubert et al., 2015; Kitemann et al., 2015; Köpcke, 2015; Lafer, 2008; Schouten et al., 1998; Tran et al., 2015).

Measurement	Cultivar	CA	DCA	CA+1MCP	Reference	Year	Quality level
Physiological disorder -superficial scald	Granny Smith				Calhan et al.	2016	1- Highest
physiological disorders (watercore/internal browning)	Elstar				Köpcke et al.	2015	2- Lowest
physiological disorders (watercore/internal browning)	Gloster				Köpcke et al.	2015	Missing data
physiological disorders(internal Browning)	Braeburn				Lafer G. et al.	2008	
physiological disorders(rots)	Golden Delicious				Kittemann et al.	2015	Higher Quality level means:
physiological disorders(rots)	Jonagold				Kittemann et al.	2015	less physiological disorders
physiological disorders(rots)	Pinova				Kittemann et al.	2015	more healthy fruits %
physiological disorder(healthy fruits %)	Galaxy				Anese et al.	2020	higher firmness
physiological disorder(flesh breakdown%)	Galaxy				F.R. Thewes et al.	2020	better volatile profile
physiological disorder(flesh breakdown%)	Royal Gala				Both et al.	2017	lower mealiness%
physiological disorder(flesh breakdown%)	Royal Gala				Anese et al.	2020	higher TA
physiological disorder(flesh breakdown%)	Royal Gala				Weber et al.	2015	higher TSS
physiological disorder(flesh breakdown%)	Imperial Gala				F.R. Thewes et al.	2020	higher sensory scores
physiological disorder(flesh breakdown%)	Fuji Suprema				F.R. Thewes et al.	2020	
physiological disorder(flesh breakdown%)	Golden Delicious				F.R. Thewes et al.	2020	
physiological disorder(flesh breakdown%)	Cripps Pink				F.R. Thewes et al.	2020	
physiological disorder(healthy fruits %)	Royal Gala						
physiological disorder(healthy fruits %)	Royal Gala				Weber et al.	2015	
physiological disorder(healthy fruits %)	Galaxy				F.R. Thewes et al.	2020	
physiological disorders(Skin spots)	Elstar				Köpcke et al.	2015	
Firmness (kg/cm)	Braeburn				Lafer G et al.	2008	
Firmness (kg/cm)	Elstar				Köpcke et al.	2015	
Firmness (kg/cm)	Elstar				Köpcke et al.	2015	
Firmness (kg/cm)	Gloster				Köpcke et al.	2015	
Firmness (kg/cm)	Gloster				Köpcke et al.	2015	
Firmness (kg/cm)	Golden delicious				Gabioud Rebeaud et a 2015		
Firmness (kg/cm)	Golden Delicious				Kittemann et al.	2015	
Flesh Firmness (N)	Granny Smith				Calhan et al.	2016	
Firmness (kg/cm)	Jonagold				Kittemann et al.	2015	
Firmness (kg/cm)	Jonagold				Köpcke et al.	2015	
Firmness (kg/cm)	Jonagold				Köpcke et al.	2015	
Firmness (kg/cm)	Pinklady				Aubert et al.	2015	
Firmness (kg/cm)	Pinova				Kittemann et al.	2015	
Firmness (kg/cm)	GreenStar						
Flesh Firmness (N)	Imperial Gala						
Flesh Firmness (N)	Fuji Suprema						
Flesh Firmness (N)	Golden Delicious				F.R. Thewes et al.	2020	
Flesh Firmness (N)	Cripps Pink				F.R. Thewes et al.	2020	
Flesh Firmness (N)	Braeburn				S.F.P. Schmidt et al.	2020	
Flesh Firmness (N)	Fuji				F.R. Thewes et al.	2017	
Flesh Firmness (N)	Galaxy						
Flesh Firmness (N)	Galaxy						
Flesh Firmness (N)	Royal Gala				Weber et al.	2015	
Flesh Firmness (N)	Royal Gala				Both et al.	2017	
Flesh Firmness (N)	Royal Gala				Anese et al.	2020	
Mealiness%	Galaxy						
Mealiness%	Galaxy						
Mealiness%	Royal Gala						
Mealiness%	Royal Gala						
TA	Braeburn				Lafer G et al.	2008	
TA	Braeburn						
TA	Golden delicious						
TA	Granny Smith				Calhan et al.	2016	
TA	Pinklady				Aubert et al.	2015	
TA	Royal Gala				Anese et al.	2020	
TA	Royal Gala				Both et al.	2017	
TA	Royal Gala				Weber et al.	2015	
TA	Galaxy				Anese et al.	2020	
TA	Greenstar				D.T. Tran et al.	2015	
TA	Imperial Gala				F.R. Thewes et al.	2020	
TA	Fuji Suprema				F.R. Thewes et al.	2020	
TA	Golden Delicious				F.R. Thewes et al.	2020	
TA	Cripps Pink				F.R. Thewes et al.	2020	
TA	Elstar				Köpcke et al.	2015	
TA	Elstar						
TA	Gloster						
TA	Gloster						
TA	Jonagold				Köpcke et al.	2015	
TA	Jonagold						
TSS	Braeburn						
TSS	Braeburn						
TSS	Golden delicious						
TSS	Granny Smith				Calhan et al.	2016	
TSS	Pinklady				Aubert et al.	2015	
TSS	Royal Gala						
TSS	Royal Gala				Anese et al.	2020	
TSS	Royal Gala				Weber et al.	2015	
TSS	Imperial Gala				F.R. Thewes et al.	2020	
TSS	Fuji Suprema						
TSS	Golden Delicious						
TSS	Cripps Pink						
TSS	Royal Gala						
Volatile Profile	Royal Gala						
Volatile Profile	Royal Gala						
Volatile Profile	Fuji				F.R. Thewes et al.	2017	
Volatile Profile	Galaxy				F.R. Thewes et al.	2020	
Volatile Profile	Braeburn				S.F.P. Schmidt et al.	2020	
Volatile Profile	Pinova				Antonio Raffio et al	2009	
Volatile Profile	Red delicious				Ciesa et al.	2013	
Volatile Profile	Galaxy				Anese et al.	2020	
Overall texture (1-5)	Jonagold				Kittemann et al.	2015	
Overall texture (1-5)	Pinova				Kittemann et al.	2015	
Sensory overall liking -taste (1-5)	Jonagold						
Sensory overall liking -taste (1-5)	Pinova						
Sensory overall liking -taste (1-5)	Greenstar						
Sensory Acid	Elstar						
Sensory Aroma	Elstar				Schouten et al.	1997	
Sensory Crisp	Elstar				Schouten et al.	1997	
Sensory crunchiness (9point)	Pinklady				Aubert et al.	2015	
Sensory Firmness	Elstar				Schouten et al.	1997	
Sensory firmness (9point)	Pinklady				Aubert et al.	2015	
Sensory flavor (9point)	Pinklady				Aubert et al.	2015	
Sensory odor 9point	Pinklady				Aubert et al.	2015	
Sensory Score (total)	Braeburn				Lafer G et al.	2008	
Sensory Sweet	Elstar				Schouten et al.	1997	
Purchase preference (0,1)	Jonagold				Kittemann et al.	2015	
Purchase preference (0,1)	Pinova				Kittemann et al.	2015	

Figure1. Summary of quality levels for physiological, instrumental, and sensory

quality attributes based on a literature review

In comparison to CA storage, DCA generally demonstrated a promising effect in reducing internal browning. (Lafer, 2008) reported an average of more than 46% reduction in internal browning in DCA than in CA (shown in Figure 1). However, the usage of 1-MCP treatments was reported as having no influence on water core dissipation rate (Neuwald et al., 2012), and in (Köpcke, 2015) study, 1-MCP treatment even increased the internal browning in ULO storage and water core incidence in DCA at 2 and 3.5°C. Similarly, 1-MCP+CA treatment also substantially promoted internal browning on an average of 44-53% increase than CA and DCA conditions (Lafer, 2008). Furthermore, DCA and CA+1MCP also demonstrated better ability in keeping lower fresh breakdown %, maintaining higher healthy fruit %, and keeping fruit flesh firmness than CA treatment (Anese et al., 2020; Aubert et al., 2015; Köpcke, 2015; Lafer, 2008; Thewes et al., 2020; Weber et al., 2015).

1-MCP treated apples also maintained a better titratability acidity than untreated DCA or CA storage (Aubert et al., 2015; Gabioud Rebeaud et al., 2015; Köpcke, 2015; Schmidt et al., 2020). In an elevated higher temperature study (3.5- 10°C), (Köpcke, 2015) concluded that 1-MCP treated fruit stored in DCA maintained better firmness and titratability acidity than 1-MCP+CA or untreated apples stored in DCA, and fruit firmness was even superior to those stored in CA (1.4+ 0.1kPa O₂) at 2°C. Total soluble solids were generally maintained across different treatments and the results were depending on cultivars.

1-MCP treatment was reported with the worst aroma profile across all the literature, consistently. This is likely because 1-MCP application (Harb et al., 2011) reduces gene expression of a key enzyme, alcohol acyltransferase (AAT), which is responsible for esterification of alcohol and acyl-CoAs to ester, a critical volatile compound in apples. The sensory liking scores for DCA and CA+1MCP were very similar and slightly better than CA treatment, but the results seem to be highly dependent on

cultivar types. In addition, due to the limited amount of research available for consumer sensory quality and liking scores, it is relatively hard to draw a conclusion here

3.2 Sensory Center evaluation:

A summary of the sensory evaluation result is provided to complement the current research gap in the literature review in the following sections.

3.2.1 Demographics and Purchasing Behavior

Demographics information and purchasing behavior were summarized in Table 3 and Figure 2. Panelists from each test vary from 80-84 with an age range of 18-68. All panelists were frequent apple consumers, eating apples at least one time per week. The top three regularly purchased apples were Honeycrisp, Fuji, and Gala.

Cultivar	What kind of apples do you regularly buy?	
	Minimum (%Panelists)	Maximum (%Panelists)
Honeycrisp	61.70%	67.50%
Fuji	50.00%	55.40%
Gala	48.10%	53.80%
Granny Smith	27.20%	35.00%
Empire	22.60%	30.00%
Cortland	21.00%	28.90%
Golden Delicious	11.30%	22.60%
Red Delicious	13.10%	17.50%
I don't know.	8.40%	13.10%
Crispin	6.20%	8.80%
Jonagold	3.60%	6.30%
Braeburn	2.40%	3.70%

Table3. Regularity of purchased apple cultivars for all panelists

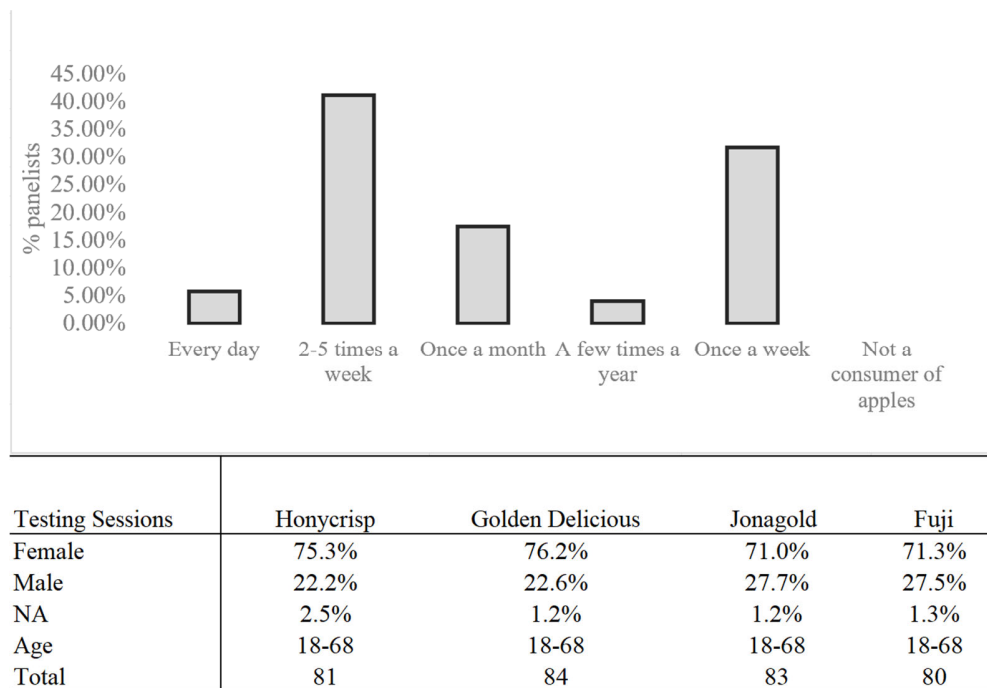


Figure 2. Summary of panelists demographic data and their apple purchasing frequency

3.2.2 Nine-point Hedonic Scale

Panelists provided liking scores for the overall and individual sensory characteristics of apples. Based on the linear mixed model (Table 4.), it was obvious that consumer liking scores varies by the cultivar effect significantly ($p < 0.05$) for overall liking, aroma liking, flavor liking, texture liking, and appearance liking. Honeycrisp and Jonagold were the most liked apples, while Golden delicious was the least liked apple (Table 5).

Parameters	Source	Numerator df	Denominator df	F	Sig.
Overall Liking	Cultivar	3	896.534	8.810	0.000
	Treatment	2	890.558	1.398	0.248
	Cultivar * Treatment	6	890.558	0.982	0.436

Aroma Liking	Cultivar	3	895.399	12.316	0.000
	Treatment	2	889.814	5.534	0.004
	Cultivar * Treatment	6	889.814	1.716	0.114
Flavor Liking	Cultivar	3	896.566	6.154	0.000
	Treatment	2	890.759	0.177	0.838
	Cultivar * Treatment	6	890.759	0.820	0.555
Texture Liking	Cultivar	3	897.603	15.341	0.000
	Treatment	2	891.481	15.910	0.000
	Cultivar * Treatment	6	891.481	3.445	0.002
Appearance Liking	Cultivar	3	895.945	87.463	0.000
	Treatment	2	890.340	22.295	0.000
	Cultivar * Treatment	6	890.340	14.280	0.000

Table 4. Linear mixed model parameters for overall and individual sensory attributes

Cultivar	Mean	Std. Error	95% Lower Bound	95% Upper Bound	p<0.05 Significant
Fuji	6.612	0.103	6.409	6.815	bc
Golden Delicious	6.556	0.101	6.357	6.754	c
Honeycrisp	7.150	0.103	6.948	7.351	a
Jonagold	6.964	0.101	6.765	7.163	ab

Table 5. Overall liking scores comparison among different cultivars

Even though the treatment effect was not significant in the overall liking scores, but it significantly impacted the aroma liking, texture liking, and appearance liking.

The interaction effect was significant in the texture liking and appearance liking scores, indicating the relationship between cultivars on the texture and appearance liking scores were different depending on variations in storage treatments.

To better understand the treatment effect and interaction effect, in addition to the model, pairwise comparisons of mean liking scores across treatment for four cultivars were visualized in Figure 3a, using Least Significant Difference with a mean difference significant at 0.05 level, and the results after Bonferroni correction were shown in Figure 3b and Table 6.

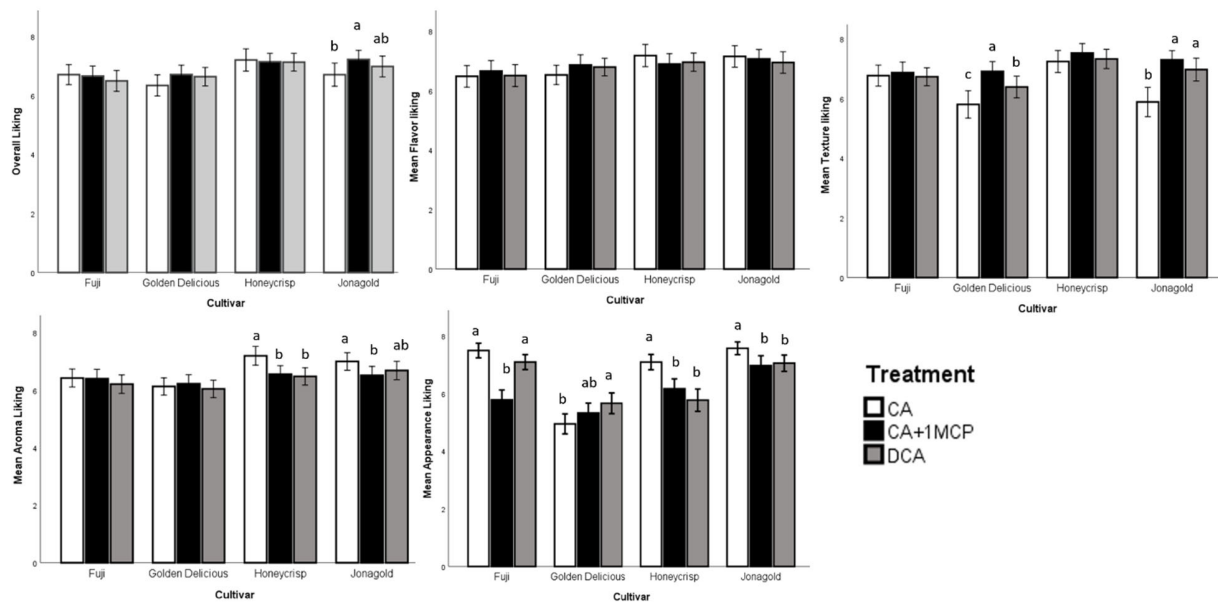


Figure 3a. Mean liking scores from different treatments and cultivars

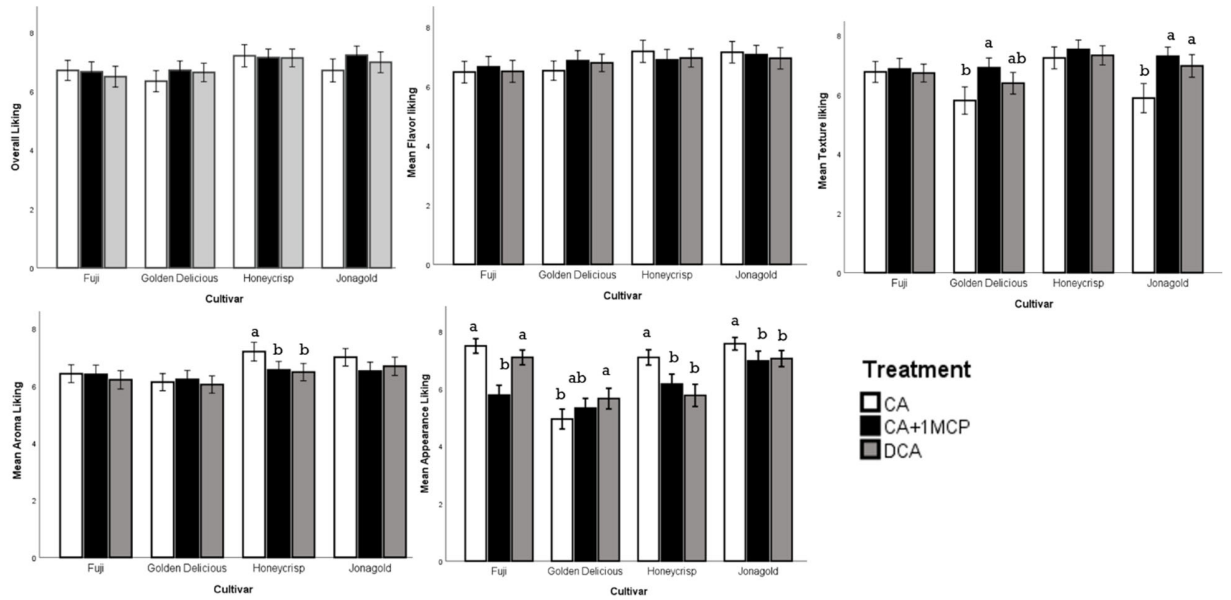


Figure 3b. Mean liking scores from different treatments and cultivars -with Bonferroni correction

Cultivar	Ttreatment	Mean	Std. Error	95% Lower Bound	95% Upper Bound	p<0.05 significant
Overall Liking						
Fuji	CA	6.700	0.172	6.363	7.036	
	CA+1MCP	6.650	0.172	6.313	6.986	
	DCA	6.487	0.172	6.151	6.824	
Golden Delicious	CA	6.333	0.167	6.005	6.662	
	CA+1MCP	6.702	0.167	6.374	7.031	
	DCA	6.631	0.167	6.302	6.960	
Honeycrisp	CA	7.195	0.170	6.860	7.530	
	CA+1MCP	7.133	0.170	6.799	7.468	
	DCA	7.121	0.170	6.786	7.455	
Jonagold	CA	6.699	0.168	6.368	7.030	
	CA+1MCP	7.217	0.168	6.886	7.548	
	DCA	6.976	0.168	6.646	7.307	
Texture Liking						
Fuji	CA	6.763	0.186	6.397	7.128	
	CA+1MCP	6.863	0.186	6.497	7.228	
	DCA	6.725	0.186	6.359	7.091	
	CA	5.798	0.182	5.441	6.155	b

Golden Delicious	CA+1MCP	6.905	0.182	6.548	7.262	a
	DCA	6.381	0.182	6.024	6.738	ab
Honeycrisp	CA	7.234	0.185	6.871	7.598	
	CA+1MCP	7.518	0.185	7.155	7.882	
	DCA	7.321	0.185	6.957	7.684	
Jonagold	CA	5.880	0.183	5.520	6.239	b
	CA+1MCP	7.289	0.183	6.930	7.648	a
	DCA	6.964	0.183	6.605	7.323	a
Flavor Liking						
Fuji	CA	6.474	0.174	6.133	6.815	
	CA+1MCP	6.649	0.174	6.308	6.990	
	DCA	6.499	0.174	6.158	6.840	
Golden Delicious	CA	6.524	0.170	6.191	6.857	
	CA+1MCP	6.857	0.170	6.524	7.190	
	DCA	6.786	0.170	6.453	7.119	
Honeycrisp	CA	7.170	0.173	6.831	7.509	
	CA+1MCP	6.886	0.173	6.547	7.225	
	DCA	6.948	0.173	6.609	7.287	
Jonagold	CA	7.144	0.171	6.809	7.480	
	CA+1MCP	7.060	0.171	6.725	7.395	
	DCA	6.940	0.171	6.605	7.275	
Aroma Liking						
Fuji	CA	6.419	0.158	6.110	6.729	
	CA+1MCP	6.394	0.158	6.085	6.704	
	DCA	6.207	0.158	5.897	6.516	
Golden Delicious	CA	6.131	0.154	5.829	6.433	
	CA+1MCP	6.226	0.154	5.924	6.529	
	DCA	6.048	0.154	5.745	6.350	
Honeycrisp	CA	7.191	0.157	6.883	7.499	a
	CA+1MCP	6.549	0.157	6.241	6.857	b
	DCA	6.475	0.157	6.167	6.783	b
Jonagold	CA	7.001	0.155	6.696	7.305	
	CA+1MCP	6.519	0.155	6.214	6.823	
	DCA	6.687	0.155	6.383	6.991	
Appearance Liking						
Fuji	CA	7.485	0.160	7.170	7.799	a
	CA+1MCP	5.772	0.160	5.458	6.087	b
	DCA	7.085	0.160	6.770	7.399	a
Golden Delicious	CA	4.940	0.156	4.633	5.248	b
	CA+1MCP	5.321	0.156	5.014	5.628	ab
	DCA	5.655	0.156	5.348	5.962	a
Honeycrisp	CA	7.085	0.159	6.772	7.397	a

	CA+1MCP	6.159	0.159	5.846	6.471	b
	DCA	5.764	0.159	5.451	6.076	b
Jonagold	CA	7.568	0.157	7.259	7.877	a
	CA+1MCP	6.966	0.157	6.657	7.275	b
	DCA	7.050	0.157	6.741	7.359	b

Table 6. Mean differences between CA, CA+1MCP , and DCA for four cultivars

Golden Delicious and Jonagold stored in CA received the lowest overall liking scores among the three storage treatments, but CA stored Fuji and Honeycrisp received the highest overall liking scores in comparison with DCA and CA+1MCP methods. Nevertheless, none of these score differences were significant. The treatment effect had no impact on overall liking scores in our test.

However, the treatment effect and interaction effect were significant for the texture liking score. Golden Delicious and Jonagold stored with CA condition received the significantly lowest texture liking scores. CA+1MCP consistently received the highest texture liking scores for all four cultivars.

The treatment effect significantly impacted the aroma liking scores. CA storage promoted the highest aroma liking scores in Fuji, Honeycrisp, and Jonagold, especially a significant result for Honeycrisp. The aroma liking differences could potentially be contributed by the aroma volatile reductions induced by the inhibition effect of 1-MCP application (Anese et al., 2020; Thewes et al., 2015). (Thewes et al., 2020) also reported that 1-MCP application suppressed the volatile compound accumulation, especially ester formation. Moreover, (Both et al., 2017; Thewes et al., 2017) reported DCA-CF (DCA based on chlorophyll fluorescence) reduced fruit ester production or had a lower volatile compound production, and a higher level of key volatiles were found for apples stored in regular CA than DCA-CF. In contrast, fruit

stored under DCA based on respiratory quotient (DCA-RQ) showed a better volatile profile than CA, ULO, and DCA-CF (Anese et al., 2020; Thewes et al., 2017).

Appearance liking scores were significantly influenced by cultivar, treatment, and their interaction effects. The appearance liking scores between DCA and CA-1MCP were only significantly different for Fuji apples, and all other cultivars received similar scores. CA+1MCP and DCA maintained better appearance scores than CA for Golden Delicious but provided significantly lower scores than CA stored Honeycrisp and Jonagold.

Overall, DCA and CA-1MCP provided similar hedonic results in overall liking, flavor liking, texture liking, and aroma liking, suggesting that DCA can be a potential replacement for CA+1MCP for achieving similar hedonic results.

3.2.3 JAR

JAR scale data provided supplemental information explaining the essential reasons that reduce the liking scores of the product. Higher weighted mean drop scores were observed in CA stored apples for texture-related attributes, such as not crisp enough and flesh too soft for Golden Delicious and Jonagold and skin too tough for Honeycrisp. These high penalty scores could potentially explain why consumers provided significant low texture liking scores on the nine-point hedonic scale for CA stored apples. This result aligned with multiple other papers, suggesting CA+1MCP and DCA possess better ability to maintain the texture of apples during long-term storage than CA (Anese et al., 2020; Çalhan et al., 2016; Kitemann et al., 2015; Lafer, 2008; Mditshwa et al., 2018).

Furthermore, CA stored apples also tend to receive higher liking scores in aroma scores. The combination of a softer flesh and higher aroma liking scores for CA storage could suggest that CA stored apples were at a different ripening stage than those of DCA and CA+1MCP. This is because a firmer fruit generally is less ripe, more acidic, and described as grassy/stalky aroma and flavor due to the presence of aldehyde, while much riper fruits tend to have lower acidity, softer texture, and fruity aroma and flavor because the presence of ester compound in its volatile profile (Harker et al., 2003). In addition, (Streif et al., 2010) suggested that consumers seem to prefer more crisp, firm, and juicy apples with less aroma than soft but more aromatic apples.

Consumers generally think Fuji and Honeycrisp apples were not sweet enough, regardless of storage treatments. DCA stored Fuji and Jonagold received the highest penalty for not being sweet enough and too sour in comparison with those stored in CA+1MCP and CA. DCA stored Honeycrisp was too green which could be a possible explanation for the significantly lower appearance liking scores in comparison with CA. Similarly, (Tran et al., 2015) reported an increase in a* value (higher a* value provides redder product) and increased in b* value (higher b* value, yellower the product) for CA than DCA after 7 and 10 months of storage. A less red DCA product can be better explained that DCA maintained a lower oxygen storage environment and was able to delay the ripening effect of fruit by inhibiting senescence-related gene expression which resulted in a retarded biosynthesis of carotenoids (Tran et al., 2015).

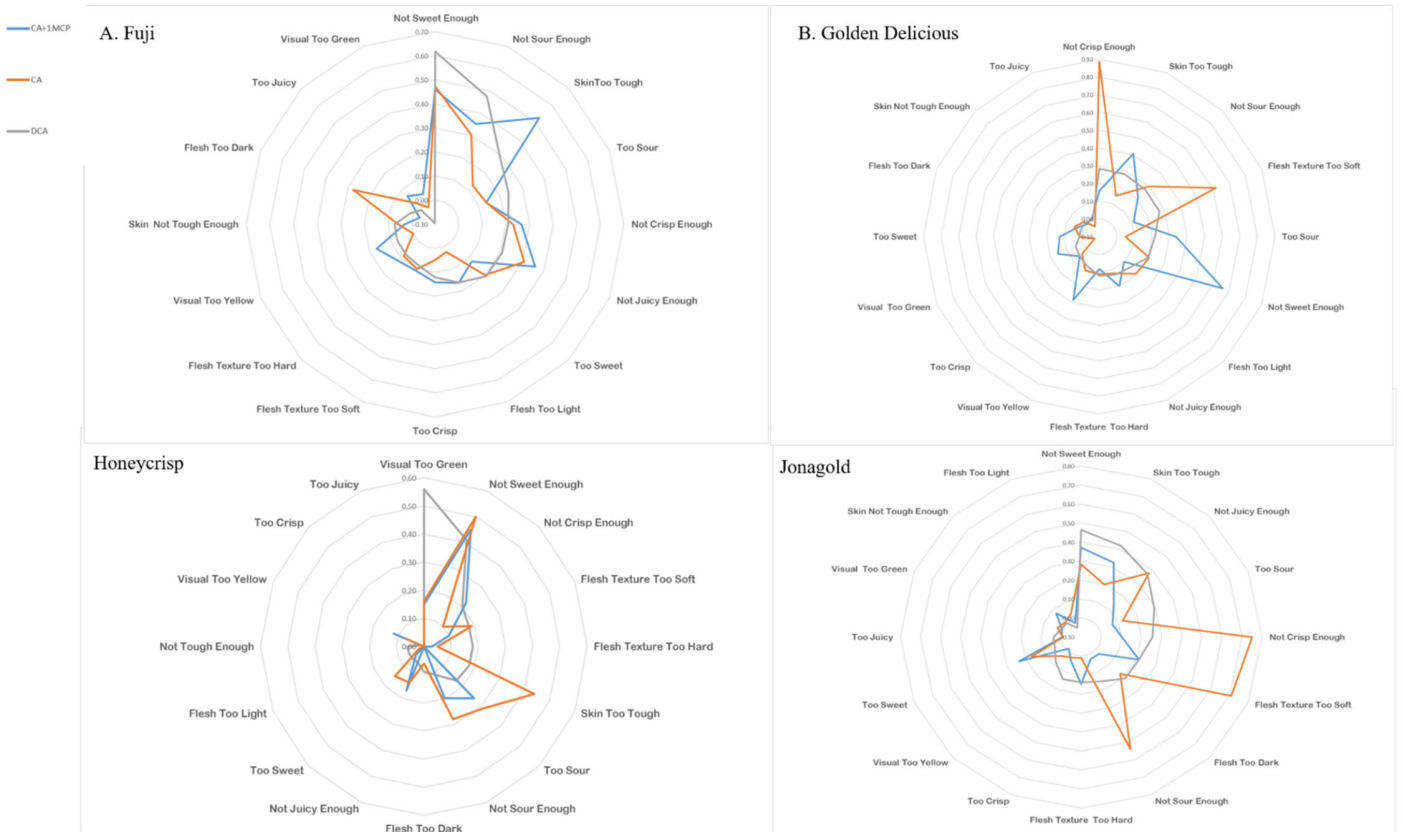


Figure 4. weighted mean drop scores for four cultivars stored in different conditions

CHAPTER 4: CONCLUSIONS

Controlled atmosphere, 1-MCP, and dynamic controlled atmosphere are all popular postharvest technology that can help to preserve apple physiological and sensory qualities. However, controlled atmosphere and dynamic controlled atmosphere have advantages in handling organic apples when compared with the 1-MCP application, which will become more essential as consumers become more concerned about chemical treatment.

When selecting proper technology, special cultivars or species could perform variously under different applications. Therefore, during the storage technology selection process, it is critical for producers to understand which sensory characteristics the targeted consumer would value more. Even though DCA and CA-1MCP do not always provide higher liking scores than CA, DCA and CA-1MCP provided similar hedonic results in overall liking, flavor liking, texture liking, and aroma liking, suggesting that DCA can be a potential replacement for CA+1MCP to achieve similar hedonic results. On the other hand, CA provided better aroma liking scores, appearance liking scores, and lower texture liking scores in most of the tested cultivars, as in comparison with DCA and CA+1MCP. To help compensate for the aroma inhibition effect from DCA-CF and CA+1MCP, DCA-RQ (with 1.5kPa O₂) was reported to maintain a better volatile profile than CA and a similar flesh firmness to DCA+1MCP (Anese et al., 2020). Future consumer sensory studies can select to test a different DCA technology with the basis on respiratory quotient to better supplement this study.

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