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Recent developments on dynamic controlled atmosphere storage of apples—A review

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ABSTRACT

The potential of dynamic controlled atmospheres (DCA) as a non-chemical treatment for maintaining the postharvest quality of apples during long-term cold storage has been an interest of researchers for decades. This article reviews the recent developments in DCA technology for storage of apples. The effects of DCA on physiological disorders, physico-chemical and sensory quality are discussed. Moreover, negative effects associated with DCA technology are also discussed. The study has shown that DCA maintains apple postharvest quality by reducing respiration rate and ethylene production. Ethylene-mediated physiological disorders such as superficial scald are completely suppressed by DCA storage. However, the effect of DCA on bitter pit incidence needs further investigation. The review also showed that fruit firmness and colour retention is considerable high in DCA stored apples. Although DCA maintains both the physico-chemical and organoleptic quality of apples, the high risk of CO_2 and low O_2 injury in DCA stored fruit remains a concern. Further research is required to refine and improve the DCA technology in order to minimize the risk of CO_2 and low O_2 injury during longterm storage.

1. Introduction

Apples (*Malus x domestica Borkh*) are globally one of the most commonly consumed fresh fruits. Approximately 64.6 million tons are consumed annually (USDA, 2017). This fruit is a rich source of bioactive compounds including vitamins, organic acids, phenolics and antioxidants. However, due to their relatively high perishability, apples are highly susceptible to storage disorders during long-term storage, to avoid postharvest losses and increase marketability during the window period, the fruit is kept in cold storage at around 0 °C for several months. However, long-term cold storage also triggers the development of physiological disorders such as superficial scald, watercore and internal browning (Lurie & Watkins, 2012). Chemical treatments such as diphenylamine (DPA) and 1-methylcyclopropene (1-MCP) have commonly been used for controlling physiological disorders and extending storability of apples (Isidoro & Almeida, 2006; Jung & Watkins, 2008). These chemicals control physiological disorders by suppressing the production of ethylene and certain harmful volatiles such as α-farnesene, conjugated trienols (CTols) and 6-methyl-5-hepten-2-one (MHO) which are commonly known for compromising the quality of stored apples. Notably, these chemicals are also effective in retaining fruit quality attributes such as firmness, colour and titratable acidity (Jung & Watkins, 2008). However, the negative effects associated with chemical treatments have restricted their use in many countries. For instance, a number of ecotoxicological studies have linked DPA with potential hazards to aquatic environments and some animals (Drzyzga, 2003). Moreover, there is a growing concern that DPA could be carcinogenic to humans. As a result, recent postharvest research has focused on developing non-chemical treatments for long-term storage of apples.

Controlled atmospheres (CA) and initial low oxygen stress (ILOS) are some of the common non-chemical postharvest treatments used by the pome industry (Sabban-Amin, Feygenberg, Belausov, & Pesis, 2011; Zanella, 2003). These technologies are known for reducing ethylene biosynthesis and respiration rate, the key biochemical processes during fruit storage (Wright, Delong, Arul, & Prange, 2015). Reduced superficial scald and greasiness incidence have been reported in fruit stored under low oxygen atmospheres (DeLong, Prange & Harrison, 2004). Although low oxygen storages (LOS) offer a range of benefits, negative

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effects associated with this technology have been identified. These include low O_2 damage and high incidence of off-flavours in apples (Imahori et al., 2005; Wright et al., 2015). To improve the efficacy of LOS, dynamic controlled atmosphere (DCA) technology has been developed for controlling physiological disorders and reducing the incidence of off-flavours (Weber et al., 2015; Wright et al., 2015).

Although a considerable amount of research has recently been conducted on the effect of LOS on postharvest quality of fruit, there is currently no published review on the effect of DCA on apple fruit quality. Prange, Wright, DeLong, and Zanella (2012) reviewed the future prospects of DCA for the storage of fruits and vegetables. On the other hand, Wright et al. (2015) reviewed the progress made on improving LOS technology for the storage of apples. However, till date, no papers have extensively reviewed the effect of DCA on physiological disorders and overall quality of apples. In this review, the most recent developments in DCA technology and its effects on apple fruit quality are discussed. In addition, possible mechanisms used by DCA in controlling physiological disorders were discussed. The prospects for future research on DCA technology for the storage of apples are highlighted.

2. Dynamic controlled atmosphere (DCA) and related technologies- an overview

Postharvest technologies for the storage of apples have evolved over the years. In the last decades, there have been concerted efforts to use non-chemical treatments as opposed to synthetic and environmentally unfriendly chemicals. Static controlled atmospheres (CA) [generally > 1% oxygen (v/v)] and ultra-low oxygen (ULO) [generally < 1% oxygen (v/v)] are some of the postharvest technologies that have been developed. However, the inefficacy of CA, ULO and ILOS to control certain physiological disorders necessitated more research. These technologies are often complimented with chemical treatments such as 1-MCP to retain fruit quality (Chervin, Raynal, Andre, Bonneau, & Westercamp, 2001; Watkins, Nock, & Whitaker, 2000). DCA is the latest technology that has globally received popularity among postharvest researchers and apple fruit producers. DCA can be broadly defined as system that allows the customisation of oxygen levels at the beginning and during storage.

Recent studies have focused on the effect of DCA to control physiological disorders and maintain postharvest quality of apples (Mditshwa et al., 2017a, 2017b; Weber et al., 2015; Wright et al., 2015). Studies have demonstrated that, unlike other LOS technologies that must be complemented with chemical treatments, DCA can be used as a 100% non-chemical postharvest treatment.

The scientific basis of CA technology to store and retain the quality of fresh fruit and vegetables dates back to more than 200 years (Thompson, 2010). Delayed CA and rapid CA are the two methods used for establishing CA conditions (Wright et al., 2015). Research has demonstrated that delayed CA is highly beneficial to apple fruit quality during storage. This is due to its ability, as opposed to rapid CA, to prevent internal browning and CO_2 injury (Argenta, Fan, & Mattheis, 2000; Saquet, Streif, & Bangerth, 2002). The inefficacy of CA to completely control certain physiological disorders led to the development of ultra-low oxygen (ULO) storage technology. Notably, O_2 levels in ULO technology are below the traditional CA guidelines (Zanella, 2003; Watkins, 2008). ULO is aimed at maximizing the CA benefits. For instance, superior fruit quality has been reported in ULO (0.7 kPa–1 kPa) stored ‘Granny Smith’ (Weber, Brackmann, Anese, Both, & Pavanello, 2011; Zanella, 2003) and ‘Golden Reinders’ apples (Altisent, Echeverría, Lara, López, & Graell, 2009) compared to fruit stored at traditional CA. However, fruit maturity is the key factor influencing the ULO efficacy during long-term storage. According to Zanella (2003), ULO is more effective in reducing coreflush in optimally harvested ‘Granny Smith’ apples. The high risk of alcoholic off-flavours, resulting from reduced production of aroma volatiles is another disadvantage associated with ULO (Watkins, 2008). The static ULO cannot detect the low oxygen concentrations just above anaerobic threshold (DeLong, Prange, & Harrison, 2007; Zanella, 2003). Even though ULO atmosphere is effective in retaining apple fruit quality, the pitfalls associated with this technology warrant further research.

Initial low oxygen stress (ILOS) is another LOS technology that has recently been developed. The scientific basis of the potential of ILOS to retain apple fruit quality dates back to the early 1980s. ILOS induces a temporary low oxygen stress (approximately 0.5% oxygen for 10 days) at the beginning of storage (Van der Merwe, Combrink, & Calitz, 2001; Wang & Dilley, 2000). The ILOS is therefore based on the notion that a certain level of ethanol is beneficial to apple fruit quality during long-term storage (Zanella & Stürz, 2012). Repeated low oxygen stress (RLOS) is another postharvest treatment that has recently been adopted by some fruit producers in Italy (Fadanelli, Turrini, Zeni, & Buglia, 2013). RLOS is simply the repeated use of low oxygen stress based on ethanol evaluation during CA storage (Prange, Wright, DeLong, & Zanella, 2013). As proposed by Fadanelli et al. (2013), RLOS should be repeated for 2–3 times during cold storage. Research on ‘Red Delicious’ apples showed that RLOS has the potential of retaining quality during 6 months storage at 1.3 °C (Zanella & Stürz, 2012). In the same study, however, RLOS was not efficient for ‘Granny Smith’ apples. This suggests that RLOS treatment could be cultivar dependent. On-going research on RLOS should be widened to other cultivars; moreover, the harvest times suitable for RLOS should also be investigated.

3. DCA sensor technologies

The regularly changing gas concentrations in dynamic controlled atmospheres are monitored by sensors. Currently, there are three types of sensors used in DCA technology; chlorophyll fluorescence (CF), respiration quotient (RQ) and ethanol (ET). However, very little research has been done on RQ and ethanol, as a result, CF is the most commonly used sensor in the pome fruit industry.

3.1. Chlorophyll fluorescence sensor

The DCA-CF technology is based on the lowest oxygen level (LOL) acceptable by the fruit during cold storage (Burdon, Lallu, Haynes, McDermott, & Billing, 2008). Basically, O_2 levels change depending on fruit physiological response. This is accomplished through the non-destructive monitoring of minimum CF, which is highly sensitive to O_2 stress, by sensors (Prange et al., 2003). The risk of irreversible O_2 injury is alleviated through the automatic increase of O_2 by sensors. HarvestWatch™ (Satlantic L.P., Halifax, Nova Scotia, Canada) is the commonly used sensor for monitoring chlorophyll fluorescence of apples during storage. Recent research has demonstrated that DCA-CF is highly effective in maintaining the postharvest quality of apples (Table 1). For example, Zanella et al. (2005) compared the postharvest performance of DCA-CF and 1-MCP on ‘Granny Smith’ apples. After 6 months of cold storage and 14 days of shelf-life, the findings were comparable between the two treatments. More recently, studies on ‘Greenstar’ (Tran, Verlinden, Hertog, & Nicolaï, 2015), ‘Galaxy’ (Thewes, Both, Brackmann, Weber, & de Oliveira Anese, 2015) and ‘Royal Gala’ apples (Weber et al., 2015) have shown that DCA-CF is more effective in retaining quality compared to ULO or CA.

The efficacy of DCA-CF could be influenced by a couple of factors such as cultivar and maturity status of the fruit. For instance, DeLong et al. (2007) reported that DCA-CF failed to completely control physiological disorders and maintaining the overall quality of ‘Cortland’ apples. Although DCA could be influenced by maturity since chlorophyll degrades as the fruit ripens, studies by Mditshwa et al. (2017b) demonstrated that DCA-CF is effective in both pre-optimal and optimal harvested ‘Granny Smith’ apples. Modelling of optimum harvest times for different apple cultivars for long-term storage in DCA-CA should be explored. This is especially important for cultivars that lack the characteristic green exocarp of ‘Granny Smith’ apples.