Dynamic CA Storage of Apples: Monitoring of the Critical Oxygen Concentration and Adjustment of Optimum Conditions during Oxygen Reduction

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Abstract

The calculated respiratory quotient (RQ), based on respiration measurements, as well as the measurement of the chlorophyll fluorescence have been tested to detect the critical oxygen concentration known as anaerobic compensation point (ACP) during oxygen reduction in dynamic CA-storage (DCA). Apples of the 'Braeburn', 'Idared', 'Maigold', 'Elstar' and 'Golden Delicious' (2 harvest dates) varieties were stored in a flow-through system, where oxygen was decreased by steps until the critical level was reached. Both methods based on RQ and fluorescence signal F-α monitoring yielded identical oxygen values for ACP. The ACPs measured were at concentrations as low as 0.15-0.40 kPa, depending on the apple variety. 'Braeburn' at 0.4 kPa exhibited a higher critical oxygen level than the other varieties tested (0.15-0.30 kPa). After the critical oxygen limit was reached, the oxygen concentration was increased by about 0.1-0.3 kPa above the critical limit. In this way, the fruit were kept at oxygen levels of 0.3 kPa to 0.6 kPa for 200 days without causing physiological disorders. Fruit firmness values of DCA stored apples were generally significantly higher than in control LO stored fruit after a storage period of more than 200 days. Trials with 'Golden Delicious' (2 harvest dates) during 2 storage seasons showed that the rate of oxygen reduction, within the setup of the trials, had no influence on the level of ACP nor the fruit quality after storage. During oxygen reduction, the CO_2-concentration was held at a constant level recommended for ULO storage for one option while, for the other, CO_2-concentration was decreased proportionally to the oxygen concentration. Both variants resulted in identical values for ACP and fruit quality in terms of fruit firmness after storage.

INTRODUCTION

The concept of dynamic CA storage (DCA) involves the reduction of the oxygen level in the storage atmosphere to near the lowest level tolerated by the fruit, the so-called anaerobic compensation point (ACP). Fruit quality loss during DCA storage is presumed to be slowed down compared to normal ULO storage. Storage conditions below the critical oxygen level will cause anaerobic conditions followed by severe quality losses in stored fruit. Ideally fruit should therefore be stored just above the compensation point. The concept of dynamic CA storage is feasible, provided that low-oxygen stress of apples, due to anaerobic conditions, is reliably detectable. The follow-up of the respiratory quotient (RQ) as well as the measurement of the chlorophyll fluorescence allow non-destructive monitoring of ACP, both methods which have been evaluated in this work. ACP can be detected by a distinct increase of RQ or the fluorescence signal F-α, if the oxygen concentration in the storage atmosphere is reduced below the critical limit. The monitoring of RQ reflects the transition from the aerobic to anaerobic pathway of energy production. The increase in F-α (corresponding to F_0) may be a response to acidosis occurring in the chloroplast, which is caused by cytoplasmatic acidosis under anaerobic conditions (Prange et al., 2005b).

Furthermore, the level of critical oxygen concentration (ACP) as well as physiological disorders and fruit quality after storage were evaluated in this work in relation to apple varieties, harvest date, oxygen reduction conditions (rate of reduction,

CO_2-concentration) and storage duration.

MATERIALS AND METHODS

DCA storage trials were conducted in the years 2005/2006 with the 'Idared', 'Maigold', 'Elstar', 'Braeburn' varieties in order to evaluate the influence of variety on the level of ACP. The apples were harvested at the commercial harvest date. Furthermore, the impact of the oxygen reduction rate and CO_2-concentration during DCA storage on the ACP level was explored in two years (2006/2007 and 2007/2008) with 'Golden Delicious', using two harvest dates (the first at commercial maturity, the second at advanced maturity) (Table 1).

All DCA trials were conducted during the entire storage seasons with 10-11 kg of apples for each test container in order to simulate DCA storage in practice. The apples used for the trials originated from the orchards of the Swiss Research Station ACW in Wädenswil (Switzerland). ACP was controlled by monitoring the respiratory quotient (RQ), calculated based on respiration measurements, as well as by the hourly measurement of the chlorophyll fluorescence (F-α) using the "Harvest Watch" system (Satlantic Inc., Halifax, N.S., Canada). Apples were kept dark-adapted during the storage tests. Firmness, soluble solids and acidity measurements were taken on samples of 20 apples removed from each storage treatment and removal date (3.5 and 7 or 8 months).

CA conditions in the test containers were maintained by mixing nitrogen, oxygen and carbon dioxide by means of mass flow controllers (Brooks 5850S). Test containers were ventilated with humidified gas mixtures allowing a gas exchange in the containers of about 7 times per hour. Respiration rate was monitored daily by closing the test containers for 2-6 hours and monitoring the changes in oxygen and carbon dioxide concentration with a Micro gas chromatograph Chrompack CP2002 (Varian Inc.) (Gasser et al., 2003).

RESULTS

ACP Level and Apple Variety

Simulation of DCA storage was made at a storage temperature of 3°C for all varieties. For each variety, one test container was held at constant LO conditions (CO_2/O_2 for 'Idared' 1.5/1.0 kPa, for 'Maigold' 3.0/2.0 kPa, for 'Elstar' 3.0/2.0 kPa and for 'Braeburn' 1.0/1.5 kPa), and one container was used for step-wise oxygen reduction. DCA test containers were first held for one week at these constant LO conditions and were then exposed to oxygen reduction at a very low rate of 0.2 kPa per week. At this oxygen reduction rate, ACP was reached after 65 to 85 days of storage (total storage duration 190 days). For the 'Idared', 'Maigold' and 'Elstar' varieties, ACPs were found at concentrations as low as 0.2 to 0.3 kPa, in 'Braeburn' at 0.4 kPa. After the ACP was reached, the oxygen concentration was increased by about 0.1 to 0.3 kPa above the critical value in order to allow safe storage until the end of storage period. As shown in Figure 1 for the development of F-α and RQ for 'Braeburn', the two parameters coincided. They both showed the same reaction to the step-wise oxygen reduction, including the shoulder before the stress peak. The stress signal can successfully be detected following the time course of F-α during oxygen reduction. Fruit firmness of DCA-stored apples was significantly higher (0.5 to 1.5 N) than that of LO stored apples, with the exception of 'Elstar' where no significant difference was found. It is interesting to note that LO-stored control fruit of the 'Maigold' variety all exhibited severe superficial scald in this storage test, whereas the DCA apples of this variety, despite the high humidity in the test containers which normally promotes skin browning, did not exhibit any disorders at all.

Influence of Oxygen Reduction Conditions

The influence of the harvest date, the rate of oxygen reduction and of the CO_2 concentration were explored in the years 2006/2007 and 2007/2008 respectively with 'Golden Delicious', picked at two different harvest dates (Table 1). Step-wise oxygen reduction was repeated three times during the storage season (more than 200 days), in order to examine whether ACP changes with storage time. Before DCA storage, apples were held at RA conditions and a temperature of 1°C for one week. Oxygen concentration was then reduced to the initial ULO conditions of 3.0 kPa/1.0 kPa (CO_2/O_2) during 2 weeks. As can be seen in Table 2, the critical oxygen concentration (ACP) after the harvest and at the beginning of the storage period was generally lower in the second test year than in the first. The ACP values after 90-100 and around 200 days of storage indicate no unequivocal trends in relation to harvest date and duration of storage over the two years. The critical oxygen concentration values must, however, be interpreted with a necessary measure of caution. Oxygen reduction was step-wise in our tests so the precise values of ACP and safe levels found depend on the decrements of oxygen reduction selected. Values may differ slightly if other decrements were selected. ACP was not influenced by the rate of oxygen reduction nor the CO_2 concentration. Compared to the LO control fruit, no difference was detected with regard to physiological disorders. As in the previous year, the course of RQ and F-α coincided perfectly, as shown by two examples (Figs. 2 and 3).

The results for fruit quality after the storage were identical in the two test years. Fruit firmness of DCA apples was only slightly higher than that of the LO control fruit after a storage period of 3.5 months, but after 7 months, DCA apples were significantly firmer (0.4-1.0N) than the LO control fruit for both harvest dates and test years. Even after a shelf life at 20°C for 10 days, DCA apples were in most cases significantly firmer (0.5-0.7N) than the LO control fruit (Figs. 4 and 5). Although not significant, the acidity of DCA apples appeared to be higher than that of LO control fruit (Figs. 6 and 7).

For both test years and harvest dates respectively, the DCA “option B” with proportional CO_2 content (Table 1) tended to show lower values for fruit firmness and acidity than the other two DCA procedures after seven months of storage (Figs. 5 and 6). Obviously the higher CO_2 content has a beneficial effect on the conservation of fruit firmness and acid concentration.

DISCUSSION

For the application of DCA, it is important that the reaction of individual fruit to oxygen reduction is homogeneous. Any fruit-to-fruit variation in respiratory behaviour would guarantee that some of the fruit, if stored at the compensation point (ACP) for average apples, will be physiologically under anaerobic conditions. Previous trials (Gasser et al., 2003) conducted in the years 1999 to 2000 with individual ‘Idared’ apples showed that respiration may be different from one fruit to the other but that the turning point or ACP, where CO_2-production increases due to the increase of anaerobic respiration is identical for all fruit.

Within the selected framework of storage conditions, the CO_2 concentration and the rate of oxygen reduction had, for the ‘Golden Delicious’ variety, no influence on the ACP or on the incidence of physiological disorders. If CO_2 reduction was mandatory, then storage facilities would be obliged to invest in CO_2 scrubbers with a very high adsorption capacity, generating additional costs.

As a result of this work, it may be concluded that the critical oxygen concentration (ACP) is evidently subject to annual fluctuations and also depends on the variety. Harvesting date and duration of storage had no identifiable effect on the ACP level. ACP was at an oxygen level of 0.15 to 0.40 kPa whereas the safe oxygen concentration was at around 0.4 to 0.6 kPa, depending on the apple variety. The ACP value found for ‘Golden Delicious’ in this study is lower than that determined by Prange et al. (2005a) based on fluorescence measurement (0.5%). Schouten et al. (1997) found a critical oxygen level for ‘Elstar’ apples, based on ethanol measurement, of 0.2 to 0.3 kPa, which corresponds with the results of this study.

Monitoring of ACP by means of F-α measurements has proven an effective method for the detection of ACP in practice. However, methodological constraints such as constant measurement geometry (distance between apples and sensors) as well as the dark-adaptation of apples must be considered.

Literature Cited

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Tables

Table 1. Design of DCA tests in the years 2006/2007 and 2007/2008 for ‘Golden Delicious’ (2 harvest dates) (Initial O_2 concentration for all treatments was at 1.0 kPa).

Type of storage	Rate of O_2 reduction	CO_2 concentration
Constant LO conditions	Constant	Constant at 3kPa
Slow rate of oxygen reduction	0.2 kPa per week	Constant at 3kPa
Fast rate of oxygen reduction (A)	0.2 kPa per day	Constant at 3kPa
Fast rate of oxygen reduction (B)	0.2 kPa per day	Proportional to O_2 (3:1)

Table 2. ACP of ‘Golden Delicious’ of different harvest dates, determined based on RQ calculation and fluorescence measurement.

Type of oxygen reduction	1st harvest date			2nd harvest date		
	1	2	3	1	2	3
Test 2006/2007						
Slow rate of oxygen reduction	0.31	0.22	0.37	0.11	0.23	0.38
Fast rate of oxygen reduction (A)	0.43	0.23	0.38	0.11	0.19	0.41
Fast rate of oxygen reduction (B)	0.45	0.28	0.44	0.12	0.22	0.38
Test 2007/2008						
Slow rate of oxygen reduction	0.14	0.37	0.25	0.14	0.47	0.27
Fast rate of oxygen reduction (A)	0.15	0.36	0.25	0.11	0.47	0.27
Fast rate of oxygen reduction (B)	0.17	0.39	0.28	0.11	0.50	0.31

1= oxygen reduction at beginning of storage: 2 = oxygen reduction after 90-100 days; 3 = oxygen reduction at the end of storage (188-197 days in 2006/2007, 235-239 days in 2007/2008); A and B see Table 1.

Figures

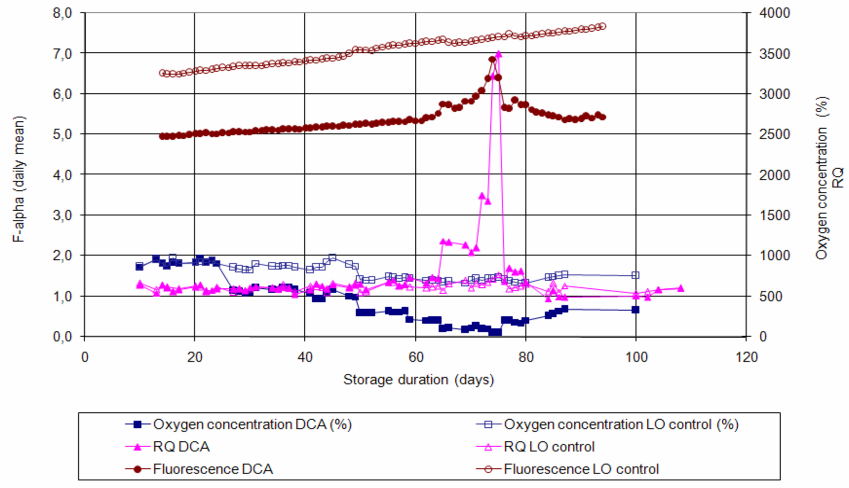

Fig. 1. Time course of RQ and F-α during simulation of dynamic CA storage of 'Braeburn' apples (2005/2006).

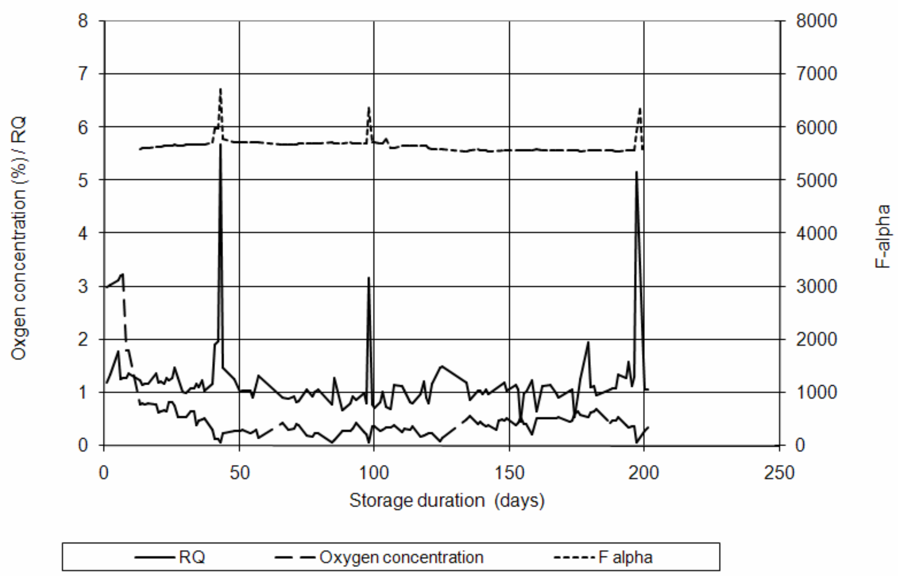

Fig. 2. Time course of RQ and F-α during simulation of dynamic CA storage of 'Golden Delicious' (first harvest date, slow oxygen reduction) (2006/2007).

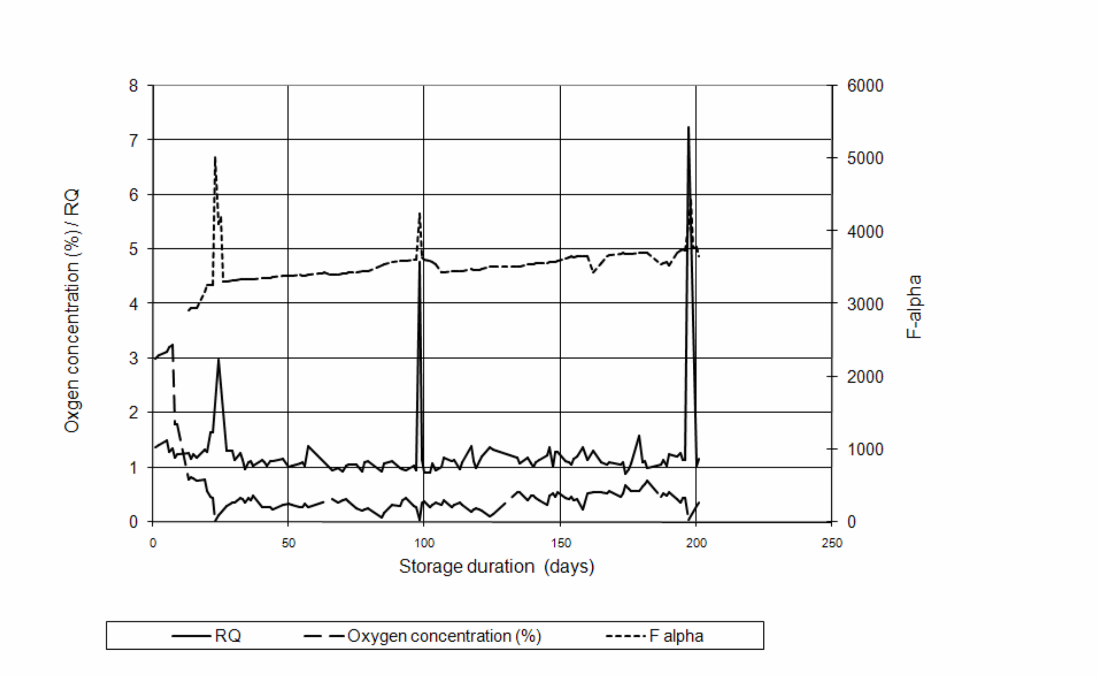

Fig. 3. Time course of RQ and F-α during simulation of dynamic CA storage of 'Golden Delicious' (first harvest date, fast oxygen reduction, procedure B) (2006/2007).

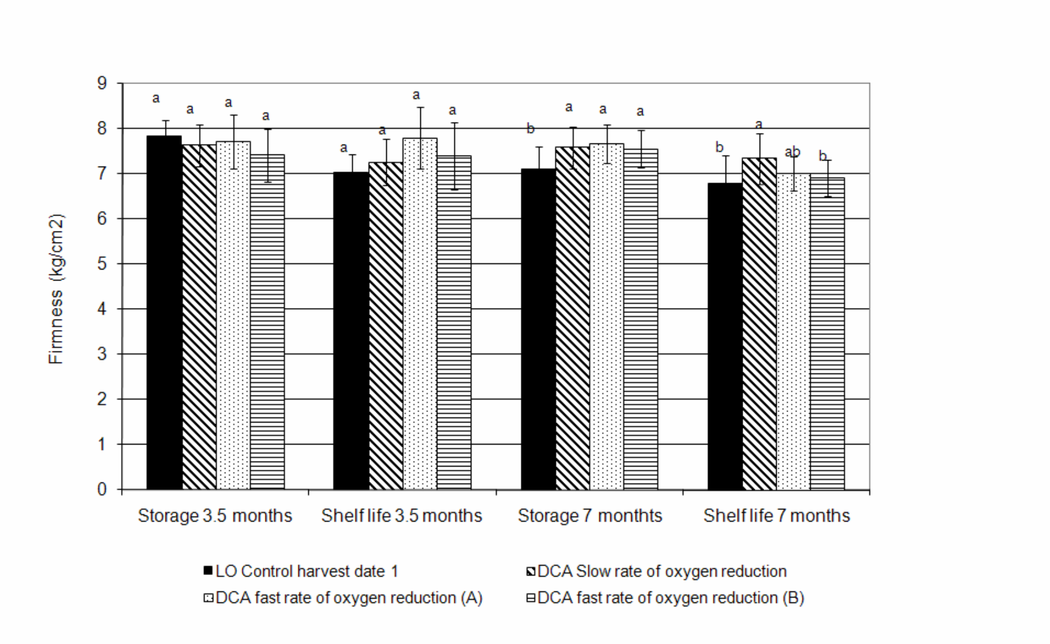

Fig. 4. Firmness of 'Golden Delicious' apples stored at LO (control) and different DCA treatments (1st harvest date) (2006/2007).

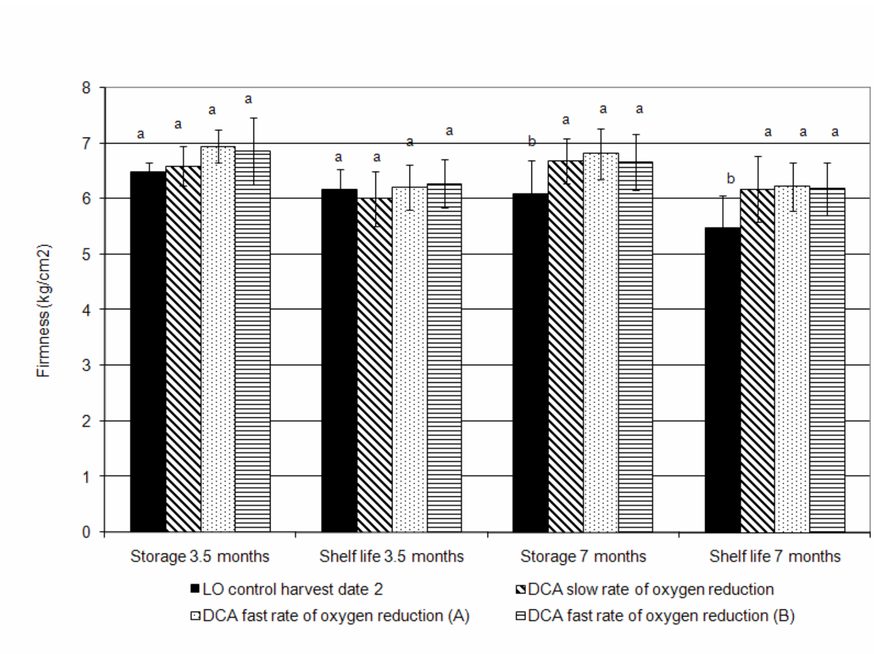

Fig. 5. Firmness of 'Golden Delicious' apples stored at LO (control) and different DCA treatments (2nd harvest date) (2006/2007).

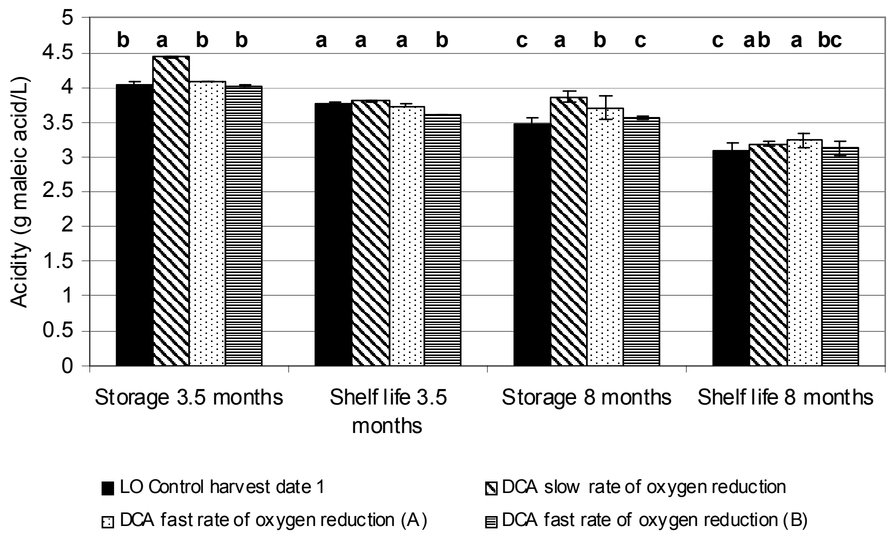

Fig. 6. Acidity of 'Golden Delicious' apples stored at LO (control) and different DCA treatments (1st harvest date) (2007/2008).

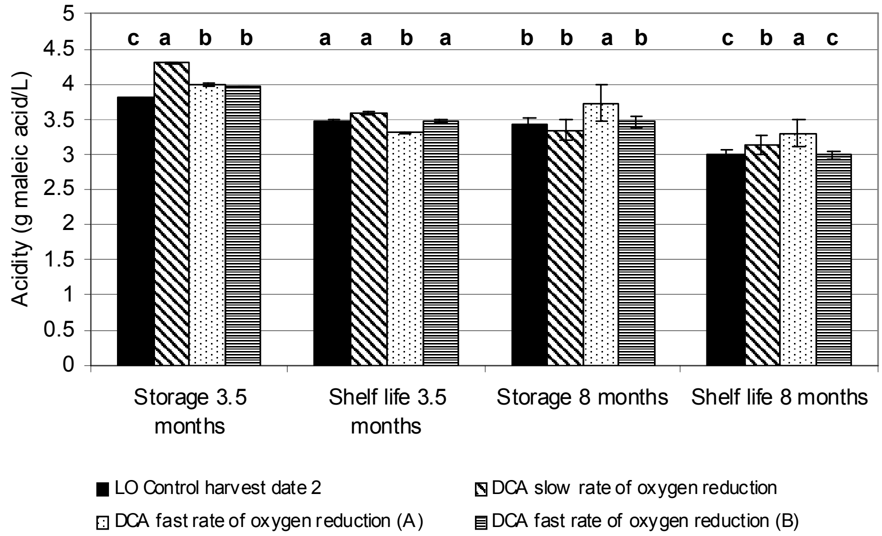

Fig. 7. Acidity of 'Golden Delicious' apples stored at LO (control) and different DCA treatments (2nd harvest date) (2007/2008).