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Economic analysis of the harvest date effects on quality and productivity of 'Fuji Suprema' apples

Luiz Carlos Argenta[1]; Rogerio de Oliveira Anese[2]; Fabio Rodrigo Thewes[3]; Marcelo José Vieira[4]; Tiago Henrique de Paula Alvarenga[2]; Sérgio Tonetto de Freitas[5]; Luiza Helena Machado Argenta[6]

1 Santa Catarina Agricultural Research and Rural Extension Company, Caçador Experimental Station, Caçador-SC, Brazil.
2 Federal Institute of Santa Catarina (IFSC), Campus Urupema, Urupema-SC, Brazil.
3 Federal University of Santa Maria, Avenida Roraima, 1000, Camobi, Santa Maria-RS, Brazil.
4 Fischer S/A Agroindústria, Rodovia SC 355, km 24, Fraiburgo-SC, Brazil.
5 Brazilian Agricultural Research Corporation (Embrapa), Petrolina-PE, Brazil.
6 Federal University of Paraná (UFPR), Curitiba-PR, Brazil.
*Corresponding author: argenta@epagri.sc.gov.br

Abstract: This study aimed to analyze the effect of harvest date on 'Fuji Suprema' apple quality, productivity, and economic profitability at harvest and after storage. Apples were harvested at the beginning of the commercial harvest window (H1), ten days after H1 (H2), and 22 days after H1 (H3) in the 2008 and 2009 growing seasons. A total of six samples with ~400 kg of fruit (~2,900 apples) each were picked at each growing season and harvest date, which were assessed at harvest (six subsamples of 100 fruit) and after 250 days of controlled atmosphere storage at 0.8 °C. The economic analysis considered fixed and variable production costs in the orchard and postharvest practices and the productivity of packaged apples (pack-out). Early harvested (H1) apples had greater flesh firmness, acidity, and lower soluble solids content than late-harvested apples (H3), both at harvest and after storage. Delaying harvest by 22 days increased the production by 10.2% due to increased fruit size but reduced the production by 3.6% due to severe sunburn and pre-harvest decay incidence. Late harvest also increased production losses due to decay by 4.4% and 10.9% during storage and shelf, respectively, but reduced production losses due to superficial scald by 17.1 to 22.7%. The net revenue (R$ ha^{-1}) is higher for apples harvested late (H3, flesh firmness of 15.6 lb and starch index of 7.1) than for apples harvested early (H1 and H2) when the fruit is marketed soon after harvest (between April and May). However, for apples marketed after long-term storage, economic profitability is maximum when harvested at an intermediate maturity stage (H2, flesh firmness of 16.4 lb and starch index of 6).

Index terms: *Malus domestica*, decay, physiological disorders, economic profitability.

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Análise econômica dos efeitos do ponto de colheita sobre a qualidade e a produtividade de maçãs 'Fuji Suprema'

Resumo: Este estudo foi conduzido para analisar o impacto da época de colheita (C) de maçãs 'Fuji Suprema' sobre sua qualidade, produtividade e rentabilidade econômica na colheita e após a armazenagem. Os frutos foram colhidos no início do período de colheita comercial (H1), após 10 dias (C2) e após 22 dias (C3) da primeira colheita, em 2008 e 2009. Em cada ano e data de colheita, foram colhidas seis amostras de ~400 kg (~2.900 maçãs), as quais foram analisadas na colheita (6 subamostras de 100 maçãs) e após 250 dias de armazenagem a 0,8 °C, sob atmosfera controlada. A análise econômica considerou custos fixos e variáveis de produção no pomar e das práticas pós-colheita e a produtividade de maçãs empacotadas. As maçãs colhidas precocemente apresentaram, na colheita e após a armazenagem, maior firmeza da polpa, maior acidez e menor teor de açúcares que as colhidas tardiamente. O atraso da colheita em 22 dias aumentou a produção em 10,2% pelo aumento do tamanho dos frutos, mas reduziu a produção em 3,6% por queimadura de sol severa e podridões pré-colheita. Adicionalmente, a colheita tardia resultou em aumento das perdas de produção por podridões em 4,4% e 10,9% durante armazenagem e prateleira, respectivamente, e reduziu as perdas de produção por escaldadura superficial em 17,1 a 22,7%. A análise econômica mostrou que a receita líquida (R$ ha^{-1}) é maior para maçãs colhidas tardiamente (C3, firmeza da polpa de 15,6 lb e índice de amido 7,1) que para maçãs colhidas precocemente (H1 e C2), quando comercializadas logo após a colheita. Entretanto, para maçãs comercializadas após longos períodos de armazenagem, a rentabilidade econômica é máxima quando colhidas em estádio de maturação intermediário (C2, firmeza da polpa de 16,4 lb e índice de amido 6).

Termos para indexação: *Malus domestica*, podridões, distúrbios fisiológicos, rentabilidade econômica.

Introduction

The harvest date is one factor that most affect apples' quality at harvest and after storage. Early-harvested apples exhibit good postharvest conservation of some aspects of quality, such as texture, but also present smaller size, less color development and aroma than late-harvested apples (KINGSTON, 1992; TOIVONEN, 2007; MAGRIN et al., 2017). Furthermore, apples harvested early may be more susceptible to some physiological disorders, such as superficial scald and bitter pit. In contrast, apples harvested at more advanced stages are more susceptible to mechanical damage, decay and some physiological disorders such as watercore, mealiness, senescent browning and CO_2 injury (ARGENTA et al., 2002; MAGRIN et al., 2017; TOIVONEN, 2007; WATKINS et al., 2005; DELONG et al., 2014; 2016; DOERFLINGER et al., 2015; CAMELDI et al., 2016; THEWES et al., 2017). For these reasons, the apple harvest date can influence the economic profitability of commercial apple production.

According to Doerflinger et al. (2015), a delay in harvesting increases fruit quality and mass; however, after a long period of storage, these advantages are nullified by the occurrence of flesh browning. In this case, the drop in financial income obtained from smaller, less reddish fruit outweighs the benefits of larger, more colorful fruit.

'Fuji Suprema' is an apple cultivar variant of 'Fuji' selected because it develops an earlier skin red color (PETRI et al., 1997). However, the maturation pattern and storage potential of the 'Fuji Suprema' apple are similar to that of other 'Fuji' variants cultivated in Brazil (ARGENTA et al., 2020). Deterioration due to decay and superficial scald incidences are the main causes of 'Fuji' apple losses after harvest in Brazil (ARGENTA et al., 2021a). Additionally, 'Fuji' apples are susceptible to CO_2 injury, requiring storage at CO_2 levels below 1% (ARGENTA et al., 1994, BRACKMANN et al., 2009). However, previous studies have shown that early harvesting and delaying the establishment of the controlled atmosphere (CA) conditions for one to four weeks after cooling can prevent CO_2 injury (ARGENTA et al., 2000). However, early harvest and delayed CA effects increase the risks of fruit losses due to higher superficial scald incidence (COLGAN et al., 1999; LURIE; WATKINS, 2012).

Considering the high susceptibility of 'Fuji' apples to decay and postharvest physiological disorders (ARGENTA et al., 2021a) and its possible relationship with the fruit maturity stage at harvest, it is important to evaluate the impact of harvest date on productivity and economic profitability of this cultivar. This analysis can contribute to adopting the best practices for harvesting and storing 'Fuji Suprema' apples in Brazil.

This study aimed to analyze the effect of harvest date on 'Fuji Suprema' apple quality, productivity, and economic profitability at harvest and after storage.

Material and Methods

Orchard and fruit samples

The experiment was conducted with 'Fuji Suprema' apples produced for two consecutive years (2008 to 2009) in a commercial orchard in Fraiburgo, Santa Catarina, Brazil. The apple trees on M.9 rootstock were planted in 2000 at a spacing of 1.0 × 3.5 m (2,850 plants per ha) and trained in a central leader system.

The apples were harvested at three dates (treatments) throughout the commercial harvest period (GONÇALVES et al., 2017). The harvests were at the beginning of the commercial harvest period (Harvest 1, 03/13/08, and 03/16/09), 11 and 10 days after the first harvest (Harvest 2), and 22 days after the first harvest (Harvest 3) in 2008 and 2009, respectively. The first harvest date was determined based on a preliminary analysis of fruit starch index. Approximately 180 apple trees were previously marked for each harvest (treatment) season in three adjacent rows.

In each year and harvest date, six samples (replications) of ~400 kg of apples (~2,900 apples per sample) were collected, which were placed in industrial containers (bins). All apples from each plant are harvested on the same day (single harvest) at each harvest date. During harvest, apples with visible (severe) symptoms of sunburn, decay, and insect damage, among other defects (industrial fruits), were sorted, placed in specific containers, and quantified the day following harvest. Six subsamples of apples with these defects were collected for each harvest date. Each subsample of apples with these defects was collected from a set of plants required to fill a bin (sample) of apples.

The day after harvest, a subsample of 100 apples was randomly collected from each sample (bin) for maturity and quality analyses. The remaining apples from each sample were analyzed after storage. A subsample of 100 average-sized apples without visual symptoms of decay or physiological disorders was collected from each sample (replication) 24 h after storage for analysis after seven days of shelf life to simulate the commercial marketing conditions. Therefore, for each year and harvest date, there were six replications of 100 apples for analyses one day after harvest, six replications of approximately 2,800 apples for analyses one day after storage, and six replications of 100 apples for analyses after storage plus seven days of shelf life conditions.

Storage

The apples were cooled and stored in a commercial storage facility under a controlled atmosphere (CA). Cooling began 24 hours after harvest, with the flesh temperature reaching 4 °C within 36 hours and 0.8 °C within 96 hours after harvest.

The storage facility was loaded with samples for this study plus ~800 tons of 'Fuji Suprema' apples for marketing. The O_2 and CO_2 concentrations were maintained at 1.5±0.2 kPa and < 0.5 kPa, respectively. The establishment of CA conditions was delayed for four weeks to avoid CO_2 damage. After storage, the apples were kept in refrigerated air (~1 °C) for 24 h before analysis. In order to simulate shelf life, the fruit were placed in cardboard trays and cardboard boxes lined with perforated low-density polyethylene bags (20 µm = 10 µm per wall), which were kept in a 100 m^3 room at 22± 1 °C for seven days.

Analysis of fruit productivity, quality and maturity

Apple productivity (kg ha^{-1}) was determined for each harvest date by weighing the bins of harvested apples, counting the number of plants from which the apples were harvested, and extrapolating the data to 2,850 plants, which corresponds to the number of plants per hectare (ha) in the orchard.

Quantity of industrial apples at harvest

Apples with visible (severe) symptoms of sunburn, decay, and insect damage, among other defects, were sorted and classified at harvest as Out of Category (not marketable for *in natura* consumption) according to the legal rules for apple classification determined by the Brazilian Ministry of Agriculture (MAPA, 2006). Out-of-category apples are typically intended for producing processed foods (juice, vinegar, and others) and, therefore, are named industrial apples. The percentage of industrial apples at harvest was determined by multiplying the mass of the subsample of industrial apples by 100 and dividing by the total mass of apples in each sample (bin).

Apple maturity and category at harvest

One day after harvest, apples from each subsample of 100 fruit were analyzed individually for maturity, mass, and category.

Flesh firmness and starch index (scale 1-9) were analyzed in a subsample of 50 representative medium-sized apples from each replication, while titratable acidity (TA) and soluble solids (SS) content were determined in two juice samples per replication collected from three sets of 10 apples as described in Argenta et al. (2020).

The category of each apple was determined by analyzing its appearance (external quality), following legal standards for apple classification (MAPA, 2006). The appearance attributes of this standard are the percentage of reddish color on the surface of the fruit and the frequency and size of visible lesions such as physiological disorders (e.g., sunburn and russeting), insect and fungal lesions including scab and decay, mechanical lesions, among others. Each fruit was placed in one of the following categories: Cat1, Cat2, Cat3, and Industry, with Cat1 being the highest quality category. Industrial fruit were not marketable for fresh consumption due to their insufficient quality, including a red color area lower than the minimum required by the legal standard (MAPA, 2006). The percentage of fruit in each category was determined by multiplying the number of fruit in each category by 100 and dividing by the total number of fruit in each subsample (100).

Quantity of industrial apples after storage and physicochemical quality after shelf life

One day after storage under CA, all apples from each sample (replication) were manually sorted by the presence or absence of any external visual defect. The defects were identified as decay and physiological disorders such as superficial scald and low calcium disorder (bitter pit and blotch pit), as described in Argenta et al. (2021a). Apples with sunburn were also identified and quantified after storage, likely because some sunburned fruit were not visualized and sorted at harvest, and some sunburn symptoms became more visible (darker) after cold storage due to the combined effects of cold plus sun damage. The percentage of apples affected by each disorder in each sample was calculated by multiplying the total mass of apples with the disorder by 100 and dividing by the total mass of apples in each sample (bin). Severely decayed apples (which could not be handled) were replaced with healthy apples of similar size for weighing.

After seven days of shelf life at 22 °C (simulation of marketing conditions), the apples were visually analyzed for the incidence of external disorders, as described above, and for internal disorders, including diffuse flesh browning and decay, as well as for flesh firmness, TA and SS content, as described in other studies (ARGENTA et al., 2020 and 2021a). The percentage of apples affected by each disorder was calculated by multiplying the number of apples affected by each disorder by 100 and dividing by the total number of apples in each subsample (100). In this analysis, all disorders present in each apple were recorded for each fruit. Therefore, it is not possible to add the percentage of apples affected by each disorder to estimate the total quantity (%) of industrial apples after shelf life.

Experimental design and statistical analysis

The experiment followed a completely randomized design, with six replications, following the 3 x 2 factorial scheme (3 harvest dates x 2 years). Each replication was composed of 100 apples for maturity analysis carried out at harvest and after storage plus shelf life (maturity, quality, and disorders, n= 100 fruit) and ~2,800 apples for analyses carried out one day after storage in CA (decay and physiological disorders). The data were subjected to analysis of variance (ANOVA) to determine the effects of the factors harvest date and production year, with the means compared by the Tukey test ($p<0.05$).

Economic analysis of the harvest date

The economic impacts of the apple harvest date in each production year were analyzed by developing a spreadsheet of business cost and revenue estimations, commonly adopted for analyzing the production cost and financial profitability of apples, as well as for comparing crop management techniques (DOERFLINGER et al., 2015; GALLARDO; ZILBERMAN, 2016; LAZZAROTTO, 2018). The economic indicators used in this analysis are described below and presented in Table 6.

The orchard's variable production cost was determined by analyzing economic data (expense sheets) for four years (2019 to 2022) from an apple production company in Southern Brazil. Expenses refer to labor, inputs, machine and equipment operations, administration, insurance, and others required for orchard maintenance. Each year, variable production cost was relativized to an average productivity of 37,800 kg per hectare (ha), corresponding to the average productivity of the first harvest date of the orchard used in the study. The orchard's fixed production cost represents 20% of the total production cost, including the annual costs of land, machinery, equipment, improvements, and orchard implementation

(LAZZAROTTO, 2018). Therefore, the production cost of the orchard used in the present study (R$ 2.02 kg^{-1}) includes variable and fixed costs relativized to an average productivity of 37,800 kg ha^{-1}.

The fixed and variable costs of postharvest practices (sort, storage, packaging) and packaging material (box and tray) represent approximately 41% of the total cost of apple production in Brazil, according to Lazzarotto (2018). However, this cost can represent approximately 50% of the total production cost when adopting a high level of technology with modern sorting machines, CA storage infrastructure for ultra-low oxygen, application of the ethylene inhibitor 1-MCP, and fruit quality management systems, according to administrative managers from the apple production companies in Santa Catarina and Rio Grande do Sul (personal communication). Therefore, the postharvest cost used for this study (R$ 1.01 kg^{-1}) corresponded to 50% of the total production cost, being R$ 0.15 kg^{-1} for sorting, R$ 0.53 kg^{-1} for packaging and packaging material and R$ 0.32 kg^{-1} for storage.

The gross revenues (R$ kg^{-1}) of apples intended for fresh consumption and processing industry (sold to the processing industry) were reported by the Brazilian Association of Apple Producers (personal communication) and represent four-year averages (2019 to 2022). The gross revenue of apples intended for fresh consumption is the average of the three legal categories (Cat1, Cat2, and Cat3, MAPA, 2006), which were sold to supermarkets immediately after harvest (April and May) or after storage (June to December). The average gross revenue of the categories was used because there was no effect of the harvest date on the frequency of apples in these categories.

Production costs and revenues (R$ ha^{-1}) were relativized to each harvest date's productivity (kg ha^{-1}). Net yields at harvest and after storage were determined by subtracting the total mass of fruit produced in the orchard from the mass of apples deteriorated by physiological disorders and decay in the orchard and after storage. The mass of industrial apples (with physiological disorders and/or decay) at harvest and after storage was relativized in kg ha^{-1} based on the percentage of industrial apples determined in experimental samples. The percentage of industrial apples after storage used for this analysis is the sum of the percentages of apples with decay, sunburn, and calcium deficiency damages. The pre-sorting cost (R$ ha^{-1}) was determined considering the net productivity of the orchard, while the cost of packaging labor and packaging material (R$ ha^{-1}) was determined considering the net productivity after pre-sorting.

Gross revenues per hectare (R$ ha^{-1}) were determined by multiplying the net yields at harvest and after storage by the gross revenue (R$ kg^{-1}). Net revenues were determined by adding the gross revenues from apples intended for the fresh consumption and processing industry and subtracting the production costs in the orchard and postharvest practices. Financial profitability was expressed as the percentage of net revenue to gross revenue. Net revenue and profitability were determined for apples sold immediately after harvest (April to May) and those sold after storage (July to December). Furthermore, net revenue and profitability were determined for apples kept for seven days at 22 °C after storage (simulation of the marketing period).

Results and Discussion

Maturity and physicochemical quality at harvest and after storage

At harvest, fruit harvested late had a higher starch index (lower starch content), higher soluble solids content, and lower flesh firmness and acidity than fruit harvested early in both years (Table 1). These characteristics of late-harvested fruit confer greater sensorial quality when offered to consumers within a few weeks after harvest (HARKER et al., 2008). Apples harvested in 2008 showed greater flesh firmness and titratable acidity at harvest than in 2009 when data from the three harvest dates were grouped. Additionally, fruit from the third harvest had higher starch content in 2009 than in the 2008 harvest season.

After storage, the fruit harvested early maintained greater flesh firmness and acidity in proportion to the differences observed at harvest in both years (Table 2), as reported in other studies for 'Gala' (ARGENTA; MONDARDO, 1994) and 'Fuji' apples (VIEIRA et al., 2018). Similar to the results observed at harvest, the average of the three harvests shows that flesh firmness and acidity were higher in 2008 compared to 2009. The SS content showed no differences after storage (data not shown).

Table 1 – Maturity indexes of 'Fuji Suprema' apple from three harvest dates (H) and two production years (Y) analyzed one day after harvest.

Harvest	Flesh Firmness (lb)			Titratable Acidity (%)			Soluble Solids (%)			Starch Index (scale 1-9)		
	2008	2009	Mean	2008	2009	Mean	2008	2009	Mean	2008	2009	Mean
1	17.4	16.5	17.0 a[I]	0.377	0.330	0.357 a	13.6	13.6	13.6 b	4.1 cA	4.8 cA	4.5
2	16.6	16.1	16.4 b	0.340	0.304	0.324 b	13.8	14.3	14.0 ab	5.9 bA	6.1 bA	6.0
3	16.0	15.0	15.6 c	0.315	0.290	0.303 b	14.5	14.5	14.5 a	6.5 aB	7.6 aA	7.1
Mean	16.7 A	15.9 B		0.340 A	0.310 B							
Harvest		****			****			**			****	
Year		****			***			ns			****	
H x Y		ns			ns			ns			****	

[I]Means followed by the same letter, lowercase vertically and uppercase horizontally, do not differ from each other according to the Tukey's test ($p<0.05$). P (Significance level by F test): ns (not significant - $P>0.05$), * ($P\leq0.05$), ** ($P\leq0.01$), *** ($P\leq0.001$), **** ($P\leq0.0001$). n=6.

Table 2 – Flesh firmness, titratable acidity, and soluble solids content of 'Fuji Suprema' apple from three harvest dates (H) and two production years (Y) analyzed after storage under CA plus seven days of shelf life. n= 6 samples of 100 fruit per bin.

Harvest	Flesh Firmness (lb)			Titratable Acidity (%)			Soluble Solids (%)		
	2008	2009	Mean	2008	2009	Mean	2008	2009	Mean
1	17.3	16.7	17.0 a[I]	0.234	0.218	0.226 a	14.1	14.3	14.2
2	17.1	15.5	16.3 ab	0.217	0.198	0.208 ab	14.2	14.7	14.4
3	16.3	14.7	15.5 b	0.209	0.180	0.195 b	14.7	15.0	14.9
Mean	16.9 A	15.6 B		0.220 A	0.199 B				
Harvest		*			**			ns	
Year		**			**			ns	
H x Y		ns			ns			ns	

[I]Means followed by the same lowercase letter vertically do not differ from each other according to the Tukey's test ($p<0.05$). P (Significance level by F test): ns (not significant - $P>0.05$), * ($P\leq0.05$), ** ($P\leq0.01$), *** ($P\leq0.001$), **** ($P\leq0.0001$).

The percentage of fruit with watercore symptoms increased by delaying harvest, presenting higher values in 2008 than in 2009 (Table 3). Apple's classification category disregards watercore, according to MAPA (2006). Therefore, the occurrence of watercore does not directly affect value or productivity. However, it may increase the risk of flesh browning and quality depreciation of 'Fuji' apples during storage (ARGENTA et al., 2002).

Table 3 - Productivity and quality of 'Fuji Suprema' apple from three harvest dates (H) and two production years (Y) analyzed one day after harvest. Incidence of apples in categories 1 (maximum quality), 2, 3 and industrial (not marketable for fresh consumption but for processed food) and apples with watercore.

	Productivity (t ha^{-1})				Industrial Fruit (%)				Fruit Mass (g)			
Harvest	2008	2009	Mean	(%)[II]	2008	2009	Mean	(%)	2008	2009	Mean	(%)
1	38.4	37.2	37.8 c[I]	0	2.0	1.7	1.8 c	0.0	141.5	137.0	139.6 b	0.0
2	40.2	38.9	39.5 b	4.6	4.2	2.9	3.6 b	1.7	150.5	145.0	148.3 a	6.2
3	42.3	41.0	41.7 a	10.3	6.8	4.2	5.5 a	3.6	153.7	152.5	153.2 a	9.7
Mean					4.3 A	2.9 B						
Harvest	****				****				****			
Year	ns				***				ns			
H x Y	ns				ns				ns			

	Watercore (%)		Category 1 (%)		Category 2 (%)		Category 3 (%)	
	2008	2009	2008	2009	2008	2009	2008	2009
1	0.0 bA	0.0 aA	30.8	36.6	39.7	41.6	26.3	18.8
2	2.6 bA	0.0 aA	30.7	35.7	33.2	41.3	33.8	20.7
3	8.3 aA	1.0 aB	25.3	30.3	32.8	42.0	37.2	23.2
Mean					35.2 B	41.7 A	32.4 A	20.9 B
Harvest	***		ns		ns		ns	
Year	***		ns		*		*	
H x Y	***		ns		ns		ns	

[I]Means followed by the same letter, lowercase vertically and uppercase horizontally, do not differ from each other according to the Tukey's test (p<0.05). P (Significance level by F test): ns (not significant - P>0.05), * (P≤0.05), ** (P≤0.01), *** (P≤0.001), **** (P≤0.0001). n=6.
[II]Difference (%) in relation to harvest 1

Productivity and value addition at harvest

The harvest delay by 22 days increased the percentage of industrial fruit segregated in the orchard due to a higher incidence of defects such as sunburn, insect damage, and decay, among others, in the two years of study (Table 3). For this reason, the delay in harvesting represented a reduction in productivity by 3.6% at harvest. However, delaying harvesting by 22 days also increased productivity by 9.7% to 10.2% due to the increase in fruit size, demonstrated by the higher total fruit mass in bins (productivity, t ha^{-1}) and individual fruit mass (Table 3).

The frequency of apples in the three marketable categories for fresh consumption was not significantly affected by harvest date in both years (Table 3). Apples harvested late have a larger area of red skin color (MAGRIN et al., 2017; TOIVONEN, 2007; WATKINS et al., 2005; DELONG et al., 2016; DOERFLINGER et al., 2015), which is one of the leading legal criteria for classifying apples into quality categories (MAPA, 2006). Therefore, an increase in the quantity (%) of apples in category 1 (highest commercial value) was expected with the delay in harvest. The stability of the apple category over 22 days of on-tree maturation is possible because 'Fuji Suprema' apples develop a red color early, in the first months of growth and development (PETRI et al., 1997). A recent study shows that delaying harvesting for 20 days increases red color by 25% to 27% for 'Fuji Mishima' and 'Fuji Select' apples and only 7% for 'Fuji Suprema' apples (ARGENTA et al., 2020). Therefore, the possible increase in 'Fuji Suprema' apple red color due to the delay in harvesting was not enough to increase the proportion of apples in category 1. The fact that 'Fuji Suprema' apples in the three harvest maturity did not differ in category demonstrates that there was no effect of the harvest date on the added value of 'Fuji Suprema' apples according to MAPA's legal quality criteria.

Productivity after storage

The harvest date affected the incidence of decay and physiological disorders after storage (Table 4). Late harvesting increased the incidence of decay (4.4%) and reduced the incidence of superficial scald (17.1%), bitter pit, and blotch pit (0.9%). As observed at harvest, the incidence of stored fruit with sunburn symptoms was 1.8% higher in late-harvested fruit compared to early-harvested fruit.

Table 4 – Incidence of decay, superficial scald, Ca deficiency disorder, shrivel, and sunburn in 'Fuji Suprema' apple from three harvest dates (H) and two production years (Y). Fruit were analyzed one day after storage under CA for 250 days. n = 6 samples of about 2,900 fruit.

Harvest	Decay (%)				Superficial Scald (%)				Calcium deficiency damage (%)				Sunburn (%)			
	2008	2009	Mean	(%)	2008	2009	Mean	(%)	2008	2009	Mean	(%)	2008	2009	Mean	(%)
1	3.0	3.2	3.1b[1]	0.0	19.7	18.1	18.9a	0.0	1.8	1.5	1.6a	0.0	2.6	0.7	1.6b	0.0
2	3.3	4.0	3.6b	0.5	2.9	9.8	6.3b	-12.6	0.5	0.7	0.6b	-1.0	2.9	1.0	1.9ab	1.5
3	7.8	7.1	7.5a	4.4	1.0	2.7	1.8b	-17.1	0.9	0.4	0.7b	-1.0	4.8	1.9	3.4a	1.8
Mean													3.42A	1.16B		
Harvest		****				**				*				**		
Year		ns				ns				ns				****		
H x Y		ns				ns				ns				ns		

[1]Means followed by the same lowercase letter vertically do not differ from each other according to the Tukey's test (p<0.05). P (Significance level by F test): ns (not significant - P>0.05), * (P≤0.05), ** (P≤0.01), *** (P≤0.001), **** (P=0.0001).

Productivity after shelf life

Apples selected for the absence of decay and physiological disorders one day after storage developed symptoms of these defects after seven days at 22 °C (Table 5). The harvest date affected the deterioration of apples during shelf life, as was during storage under CA. Delaying harvesting by 22 days increased production losses due to decay by 10.9% and reduced losses due to superficial scald by 22.7%. The incidence of apples with bitter pit, blotch pit, and "brown shoulder" disorders was not significantly affected by harvest date. The "brown shoulder" incidence was higher in fruit produced in 2009 than in 2008.

Table 5 – Incidence of decay, superficial scald, Ca deficiency damage, and "brown shoulder" in 'Fuji Suprema' apple from three harvest dates (H) and two production years (Y). Fruit were analyzed after storage under CA for 250 days plus seven days of shelf life at 22 °C. n = 6 samples of 100 fruit.

Harvest	Decay (%)				Superficial Scald (%)				Calcium deficiency damage (%)			Brown Shoulder (%)		
	2008	2009	Mean	(%)	2008	2009	Mean	(%)	2008	2009	Mean	2008	2009	Mean
1	6.8	8.5	7.6b[1]	0.0	40.1aA	14.2aB	27.1	0.0	0.51	1.12	0.82a	0.00a	0.93a	0.46
2	9.7	12.6	11.1b	3.5	11.0bA	15.8aA	13.4	-13.8	0.29	1.18	0.73a	0.00a	1.02a	0.51
3	20.1	16.9	18.5a	10.9	1.7bB	7.1aA	4.4	-22.7	0.28	0.58	0.43a	0.08a	4.57a	2.32
Mean									0.361B	0.961A		0.028B	2.169A	
Harvest		***				****				ns			ns	
Year		ns				ns				**			*	
H x Y		ns				***				ns			ns	

[1]Means followed by the same letter, lowercase vertically and uppercase horizontally, do not differ from each other according to the Tukey's test (p<0.05). P (Significance level by F test): ns (not significant - P>0.05), * (P≤0.05), ** (P≤0.01), *** (P≤0.001), **** (P=0.0001).

The higher incidence of decay in late-harvested fruit is probably due to advanced ripening, reduction in phenolic compounds, and increased cell wall degradation, which makes the fruit more susceptible to the growth and development of pathogens (NERI et al., 2019; NYBOM et al., 2020; PRUSKY et al., 2013; SUGAR, 2002), as well as due to the more prolonged exposure of fruit to pathogens in the orchard. Similar results were also reported by Cameldi et al. (2016) in 'Cripps Pink' apples after refrigerated storage for 150 days, where delaying harvesting by 32 days increased bull's eye rot from <14% to 60% (orchard 1) and 25% (orchard 2), compared to the commercial harvest date. In 'Aroma' apples, the delay in harvesting in relation to the commercial harvest date increased the percentage of rot incidence in the fruit by approximately 10% (BØRVE et al., 2013).

The production loss due to decay incidence was more significant during the shelf life than during the CA storage, regardless of the harvest date, which was also observed in previous studies (ARGENTA et al., 2021a). This result reinforces the importance of maintaining the cold chain during the transport and marketing of apples at retail, considering that refrigeration reduces deterioration due to rot during this period (ARGENTA et al., 2021b). Although shelf life is traditionally simulated by keeping apples for seven days at 20 °C, in Brazil, the period between the apples' packaging date and their display on market shelves varies from 17 to 28 days; the temperature of the apples on the shelves varies greatly depending on the time of year and region of Brazil (ARGENTA et al., 2015). Therefore, the high decay incidence observed during the shelf life period in this study can be even higher under commercial conditions.

The low calcium disorders (bitter pit and blotch pit) incidence was reduced with the delay in harvest, according to the assessment carried out one day after storage (Table 4). However, at seven days of shelf life, the incidence of these physiological disorders did not differ among harvest dates, with the 2009 harvest having a higher incidence than the previous 2008 harvest.

Economic analysis

Fruit mass and the incidence of decay and physiological disorders (e.g., superficial scald) were the main variables associated with changes in productivity, depending on the apple harvesting date. The incidence of superficial scald is usually zero in apples treated with 1-MCP (1-methylcyclopropene) and stored under CA with ultra-low O_2 concentrations (ZANELLA, 2003). Therefore, in the economic analysis of the harvest date, the cost of applying the 1-MCP technology was added to the storage cost, and the reduction in productivity caused by superficial scald was disregarded.

Profitability at harvest

Net revenue increased with harvest delay for apples marketed shortly after harvest (Table 6). The variation in net revenue between the first harvest (H1) and the third harvest (H3) was R$ 5,410.43 ha^{-1} for apples sold at harvest. Profitability was 7.5%, 9.5%, and 11.9% for H1, H2 and H3 apples, respectively. This demonstrates that the gain in productivity due to higher apple fruit size is greater than the loss of productivity due to the development of defects (sunburn, insect damage, decay, and others) during fruit maturation on the tree. This increase in profitability is possibly more significant for some variants of 'Fuji' (e.g., 'Fuji Mishima') that exhibit a marked increase in red color during fruit maturation on the tree (ARGENTA et al., 2021a). This fact does not mean that all 'Fuji Suprema' apples should be harvested late and marketed shortly after harvest. It should be noted that Brazil produces approximately 1,100,000 tons of apples per year (KIST, 2019), and it would not be possible to sell the whole production at the beginning of autumn because the monthly apple consumption in Brazil is approximately 100,000 tons per month (KIST, 2019). Additionally, the excess supply of apples during this period would significantly reduce the retail sales price, and revenue would be lower than that described in Table 6.

Table 6. Estimates of economic indicators (production cost and gross revenue) in R$ kg^{-1}, apple productivity at harvest and after storage in kg ha^{-1}, production cost in R$ ha^{-1} and gross and net revenues in R$ ha^{-1} for 'Fuji Suprema' apples harvested at three maturity stages (H1, H2, H3), marketed soon after harvest and after long-term storage.

Economic indicators		Harvest H1	Harvest H2	Harvest H3
Cost of production in the orchard (R$ kg^{-1}) [/1]	A (2.02*37800/H)	2.02	1.93	1.83
Cost of pre-sorting (R$ kg^{-1})	B	0.14	0.14	0.14
Cost of packaging (service + packaging material) (R$ kg^{-1})	C	0.45	0.45	0.45
Cost of storage, including 1-MCP (R$ kg^{-1})	D	0.32	0.32	0.32
Gross revenue apple CAT1, -2 and -3, April to May (R$ kg^{-1}) [/2]	E	2.86	2.86	2.86
Gross revenue apple CAT1, -2 and -3, Jul to Dec (R$ kg^{-1})	F	3.55	3.55	3.55
Gross revenue from industrial apples (R$ kg^{-1}) [/3]	G	0.30	0.30	0.30
Productivity at harvest		**Harvest H1**	**Harvest H2**	**Harvest H3**
Total productivity (harvested in the orchard) (kg ha^{-1})	H	37,800.00	39,553.92	41,678.66
Industrial apple (kg ha^{-1}) [/3 /4]	I	680.40	1,423.94	2,292.33
Net productivity (kg ha^{-1})	J (H-I)	37,119.60	38,129.98	39,386.33
Revenue for apples marketed at harvest		**Harvest H1**	**Harvest H2**	**Harvest H3**
Cost of production at harvest (R$ ha^{-1})	K (A*H)	76,356.00	76,356.00	76,356.00
Cost of pre-sorting (R$ ha^{-1})	L (B*H)	5,143.82	5,382.50	5,671.63
Cost of packaging (service + packaging material) (R$ ha^{-1})	M (C*J)	16,837.45	17,295.76	17,865.64
Gross revenue from apples for fresh consumption (R$ ha^{-1})	N (E*J)	106,162.06	109,051.74	112,644.91
Gross revenue from industrial apples (R$ ha^{-1})	O (G*I)	204.12	427.18	687.70
Net Revenue (R$ ha^{-1})	(O+N-M-L-K)	8,028.90	10,444.67	13,439.33
Productivity after storage		**Harvest H1**	**Harvest H2**	**Harvest H3**
Industrial apples after storage (kg ha^{-1})	P	2,354.00	2,332.28	4,532.71
Industrial apples after shelf life (kg ha^{-1})	Q	3,303.64	4,613.73	7,286.47
Productivity after storage (kg ha^{-1})	R (J-P)	34,765.60	35,797.70	34,853.62
Productivity after shelf life (kg ha^{-1})	S (J-P-Q)	31,461.95	31,183.97	27,567.15
Revenue for apples marketed after storage		**Harvest H1**	**Harvest H2**	**Harvest H3**
Cost of storage, including 1-MCP (R$ ha^{-1})	T (D*J)	11,786.22	12,107.03	12,505.95
Cost of pre-sorting (R$ ha^{-1})	U (B*J)	5,051.24	5,188.73	5,359.69
Cost of packaging (service + packaging material) (R$ ha^{-1})	V (C*R)	15,769.68	16,237.83	15,809.60
Gross revenue from apples for fresh consumption (R$ ha^{-1})	W (F*R)	123,417.88	127,081.82	123,730.36
Gross revenue from industrial apples (R$ ha^{-1})	X (G*(I+P))	910.32	1,126.87	2,047.51
Net Revenue (R$ ha^{-1})	(X+W-V-U-T--K)	15,365.07	18,319.09	15,746.62
Revenue for apples marketed after shelf life		**Harvest H1**	**Harvest H2**	**Harvest H3**
Cost of packaging (service + packaging material) (R$ ha^{-1})	Y (C*S)	14,271.14	14,145.05	12,504.46
Gross revenue from apples for fresh consumption (R$ ha^{-1})	Z (F*S)	111,689.94	110,703.09	97,863.38
Gross revenue from industrial apples (R$ ha^{-1})	Z' (G*(I+P+Q))	1,901.41	2,510.99	4,233.45
Net Revenue (R$ ha^{-1})	(Z'+Z-Y-U-T-K)	6,126.76	5,417.26	-4,629.26

[/1] Cost of production in the orchard includes variable and fixed costs relativized to a productivity of 37,800 kg ha^{-1}.
[/2] Average value for apples in categories 1, 2 and 3.
[/3] Industrial apples: not marketable for fresh consumption but for processed food.
[/4] Sum of damage due to calcium deficiency, sunburn and decay.

Profitability after storage

Apple quality deterioration, primarily due to decay, resulted in lower productivity after storage. However, gross and net revenue were higher for apples commercialized after storage than those commercialized shortly after harvest. This fact reinforces the importance of extending the marketing of apples throughout the year.

For apples stored for an extended period, the productivity gain was more significant when harvested at intermediate maturity (H2), reflecting a compromise between the loss of production due to smaller size fruit in response to early harvest and the loss of production due to decay and physiological disorders incidence in the fruit in response to late harvest. In this case, net revenue was slightly higher with H2 apples, and profitability was 12.4%, 14.3%, and 12.5% for H1, H2 and H3 apples, respectively.

Profitability after shelf life

After the marketing period simulation (shelf life), the economic analysis for apple production shows that net revenue would be similar for H1 and H2 apples, and profitability would be 5.4%, 4.8%, and - 4.5% for apples from H1, H2, and H3, respectively. In this case, there would be no economic gain from producing H3 apples.

This analysis contributes to assessing the impact of the ‘Fuji Suprema’ harvest date on economic gains, although apples are always marketed to supermarkets soon after being removed from the storage environment (before shelf life). Notably, the high incidence of decay and physiological disorders during the marketing period can reduce gross revenue (R$ kg^{-1}) due to discounts from the grower to the supermarket. Additionally, the high incidence of decay and physiological disorders during marketing and in consumers’ homes can negatively affect the image and brand of the product (“value downgrade”), reducing its demand and gross revenue (R$ kg^{-1}) for the grower (KUPFERMAN, 2010; GALARDO et al., 2011) or lead to replacement by other fruit cultivars or species by consumers (HARKER et al., 2003). This result also indicates that part of the difference in sales prices to retailers and consumers (ARGENTA et al., 2015) may be applied to cover production losses during marketing.

In summary, over the 22 days of on-tree maturation, there were changes in internal quality, such as a reduction in flesh firmness (from 17 to 15.6 lb) and acidity, as well as increased SS content. However, according to the legal quality standards -based on appearance -the fruit category remained the same (MAPA, 2006), and there was no gain in marketing value of the fruit over the 22 days of on-tree maturation. However, the harvest date affects the productivity of ‘Fuji Suprema’ apples. The harvest date’s impact on harvest productivity is due to increased fruit mass (size) and deterioration due to sunburn, insects, and decay associated with late harvest. The impacts of the harvest date on productivity after storage are associated with the deterioration of apples, primarily due to decay and superficial scald. Treatment of apples with 1-MCP and/or storage under a dynamic controlled atmosphere with ultra-low O_2 inhibits the development of superficial scald (ZANELLA, 2003). Therefore, in this study, the cost of these techniques was added to the postharvest cost, and losses due to superficial scald were disregarded. The economic analysis showed that the net revenue (R$ ha^{-1}) is higher for apples harvested late (H3) than for apples harvested early (H1 and H2) when marketed soon after harvest (between April and May). However, for apples marketed after long storage periods, economic profitability is maximum when the fruit is harvested at an intermediate maturity stage, at H2, with flesh firmness of 16.4 lb and starch index 6 (1-9).

Conclusions

'Fuji Suprema' apples harvested at advanced maturity are larger and have lower flesh firmness, titratable acidity, and higher soluble solids content; they are more affected by sunburn, insect damage, and decay and less by superficial scald.

Net productivity and economic profitability are maximum for late-harvested apples (H3, flesh firmness of 15.6, and starch index of 7.1) when fruit are marketed soon after harvest.

Harvesting with intermediate maturity (H2, flesh firmness of 16.4, and starch index of 6) provides maximum productivity and economic profitability after long storage periods when associated with postharvest practices that inhibit superficial scald incidence.

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